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Levels of Selective Attention Revealed Through the Analyses of Response Time

Distributions

By

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A dissertation presented to the
Graduate School of Arts and
Sciences of Washington University
in partial fulfillment of the
requirements for the degree of
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Abstract

The present research uses a convolution of an exponential and a Gaussian (ex-Gaussian) distribution to examine the influence of experimental manipulations on components of response time (RT) distributions. Previous research has indicated that interference in the Stroop task results in an increase in the Gaussian and the exponential component of the RT distribution. Moreover, the increase in Stroop interference in older adults relative to younger adults has been shown to result from the increase in the exponential component of the ex-Gaussian. The results of two preliminary studies are reported that show that interference in two other selective attention tasks, a letter flanker and local/global task, influenced only the Gaussian component and had no effect on the exponential component of the distribution. Moreover, in contrast to the Stroop task, interference in the flanker and local/global task had a very similar influence on the components of the RT distribution for younger and older adults. Four experiments investigated the influence of different levels of selective attention on components of response time distributions and the nature of age differences in RT distributions. The results of four experiments suggested that the interference effect in the exponential component occurs when individuals are required to select attributes of a spatially integrated object as is the case in the Stroop task. When competition occurs at the level of spatial selection or response selection, interference effects are found only in the Gaussian component. These results support the notion that a more central level of selection required in the Stroop task includes a process whereby the results of processing are probabilistically checked for accuracy. This checking process results in more responses falling in the exponential

component of the RT distribution. This research also demonstrates the utility of analyses of response time distribution in providing insights into underlying cognitive processes.

Chapter I : Introduction

Interacting with the environment is difficult. Even the simplest of activities require the control of the direction of attention. Understanding how this attentional control is accomplished remains one of the central goals of cognitive psychology and associated fields such as cognitive neuroscience.

The overall goal of this research is to provide some insight into the operation of selective attention through the detailed modeling of response times. In the first chapter, I provide some discussion of the processes that underlie attentional selection and tasks that appear to tap the operation of these processes. In the second chapter, I discuss an analytic technique that provides further insight into the temporal dynamics of these selection processes. Chapter 3 examines preliminary evidence that the modeling of RT distributions might reflect the operation of different modes of selection. In Chapter 4, I provide a theoretical framework for interpreting these differences and derive predictions for the four experiments reported here. Chapter 5 reports the results of four experiments and discusses the implications of these results. Finally, in Chapter 6, I attempt to provide a unified account for results of the present experiments and other relevant studies in the literature.

Historical Background

Research addressing selective attention has, to a large extent, focused on a number of dichotomies (e.g., early versus late selection, controlled versus automatic processing, etc.). The most prominent of these dichotomies, early versus late selection, is marked by an attempt to determine *the* locus of attentional selection. Does the selection of stimuli

occur early in processing on the basis of physical/perceptual characteristics, or does it occur later in the information processing stream where stimuli may be selected based on semantic or other higher level properties? This question of the locus of selection assumes that it is possible to divide processing into a preattentive and postattentive stage.

Preattentive processing is presumably unlimited in processing capacity (or practically so) and occurs largely outside the conscious awareness of the individual. In contrast, postattentive processing is sharply limited in processing capacity and is guided by the explicit intentions of the individual.

The classic study of Cherry (1953) provided some insight into the question of how extensively information was processed before reaching the locus of selection. In this study, individuals were presented with two separate auditory streams, one in each ear. When subjects were told to attend to the message in one channel, they were able to report only general perceptual characteristics of the signal in the other channel. These results are consistent with the notion that selection occurs early and that preattentive processing was limited to the analysis of perceptual features. Results such as these were accounted for by Broadbent's (1958) model that included unlimited capacity *P system* where incoming information was analyzed based on perceptual properties (see Figure 1). Selection was conceived of as a filter that operated on the output of the *P system*. This filter allowed only information with the requisite perceptual characteristics entry to a second system where the selected signal received further analyses.

The purpose of Broadbent's filter was to stop further processing of a signal that did not have the required perceptual features and only after the filter did semantic

analyses of the signal occur. The implication is that semantic characteristics of unattended information should have no effect on the efficacy of the selection process. However, a number of studies subsequently showed that meaning level information did impact the selection process. One study (Oxford, Gray, & Wedderburn, 1960) used a dichotic listening task where an individual might be told to attend to the right auditory channel only (e.g., the right ear). If a two syllable word is presented with one syllable presented to the right channel and the other presented to the left channel, Broadbent's model predicts that attention filters out the information in the left channel and the individual only hears a nonsense syllable. If subjects reported hearing the entire word, this would provide evidence that higher level information such as the lexical status of the two syllables was processed, in contradiction to the early selection account. This study showed that individuals frequently reported hearing the word. There are several possible conclusions that one could draw from this observation. One could conclude that the idea of an attentional filter was generally correct but that selection was not perfect. Alternatively, one could push the selection stage later in the processing stream so that some semantic information could be processed preattentively and hence, influence the selection process. It is also possible that individuals may be able to switch attention rapidly between channels (see for discussion, Cowan, 1995).

Treisman's (1964) formulation took the former approach and suggested that the selection process did not completely screen out the unattended signal. Instead the unattended signal was attenuated in strength relative to the attended signal. In Treisman's theory, incoming signals could activate corresponding mental representations.

Thus, all other things being equal, selected signals resulted in stronger activation than nonselected signals. However, context could also activate representations that were related to the selected signals. If a nonselected signal is related to the current focus of attention, the attenuation may be overcome by the preactivation of the signal's corresponding representation. Thus, information outside the current focus of attention, but related to current processing, may still be processed to some later stage. Support for Treisman's filter attenuation theory comes from a series of experiments in which subjects were to shadow text in one auditory channel while ignoring speech in another channel. Treisman found that shadowing one channel was easiest when the unattended information was in a foreign language and most difficult when it was English speech with content related to that presented in the shadowed channel. Thus, it was increasingly difficult to ignore information as the unattended information became increasingly related to the attended information, as predicted by the filter attenuation account.

An alternative approach to Treisman's is to suggest that selection occurs later in processing. In this view, selection occurs relatively late in the processing stream and incoming signals may receive some semantic level processing that is preattentive (e.g., Deutsch & Deutsch, 1963). The placement of selection later in the processing stream suggests that selection may not need to act based solely on the perceptual characteristics of the stimuli. For example, Duncan (1980) conducted a series of studies where participants were presented with an array of targets (i.e., items requiring a response) and distractors (i.e., items requiring no response) and the number of targets could be zero, one, or two. If one assumes that preattentive processing is unlimited in capacity, while

postattentive processing is capacity limited, then early and late selection accounts make different predictions about the effect of multiple targets. Early selection is supposedly based on perceptual features. Because the targets and distractors were not distinguished by simple features, early selection would predict that both targets and distractors would be selected. Hence, the primary influence on performance would be the total number of stimuli. Late selection accounts might allow the target/distractor status of each stimulus to influence the selection process. This predicts that the primary effect on performance would be the number of targets only. Duncan showed that individuals experienced interference only when multiple targets were presented simultaneously in the display, supporting the late selection account.

The problem within the study of attention became how to reconcile results such as those of Duncan (1980) that suggested a late locus of selection with results such as those of Cherry (1953) that suggested an early locus of selection. Indeed, this issue of early versus late selection has not come to a resolution after 40 years of active research. There are several reasons for this state of affairs. First and foremost, the search for the locus of attentional selection rests on assumptions that may not be entirely warranted based on currently available evidence (see also Allport, 1987; 1989; Neumann, 1987; Van der Heijden, 1987; 1992).

The early/late dichotomy relied on the assumption that it would be possible to localize the operation of a single selective process. This assumption was driven largely by the general processing frameworks appearing in the early literature (e.g., Broadbent, 1958; Norman, 1968). The architecture that these theories assumed contained some

central processor whose job was to process information regardless of the domain or modality of the incoming signal. However, once one considers the neural structures upon which attention must act, the notion of a general processor begins to look less appealing. Thus, when individuals are required to make comparisons between two briefly presented displays, the particular brain areas that show activation depend on the nature and number of the dimensions in the display that were relevant (e.g., movement, color, shape, Corbetta, Miezen, Dobmeyer, Shulman, & Petersen, 1991). This indicates that the locus of selection is closely tied to the nature of the task and the type of information that is to be selectively processed.

Certainly in the behavioral literature individual theories and models have incorporated a variety of attentional mechanisms and each of these differ in how selection is achieved. For example, selection within a model of the Stroop task (Cohen, Dunbar, & McClelland, 1990) is implemented very differently from selection in a general model of object recognition (LaBerge & Brown, 1989). This is not surprising because attention in these two models has different objectives to accomplish. Part of the problem with theorizing in this area is that attentional selection has been used as an umbrella term for individual processes that have the general characteristic of control, but that implement it in ways that are domain specific and may entail different computational characteristics (see also, Kanne, Balota, Spieler, & Faust, 1996).

Two General Functions of Selective Attention

There are at least two general functions of attentional selection. One function is required for the ongoing control and coordination of processing. In this case, selection is

required for the engagement of task-appropriate cognitive processes. For example, an experimental task may require an individual to name words that appear in the center of a computer screen. To carry out this task, the cognitive system must be organized such that visual-spatial attention is allocated to the appropriate location and the brain regions responsible for processing of letter strings are activated while regions not required for task performance are either not activated or are deactivated. This type of attentional function is implemented in a number of behavioral models. For example, this function is implemented in the Supervisory Attentional System (Norman & Shallice, 1986; Shallice, 1988), as production sequences in the model Soar (Newell, 1989), and as working memory (or its subcomponents) in a myriad of other models (e.g., Baddeley, 1986; Kimberg & Farah, 1993). In neuropsychology, the traditional view is that distributed networks of the frontal lobe are crucial to the functioning of this form of attention (see for example, Passingham, 1993; Posner & Petersen, 1990; Shallice, 1988).

A second form of attentional selection includes those processes that allow the individual to orient to sources of stimulation in the environment. For example, in a cluttered room, attention has to allow for the selection of a particular region or object in the environment while ignoring other competing information. This form of selection allows for the enhanced processing of particular regions in the environment. Under this heading would be the location- and object-based models of visual selection (e.g., LaBerge & Brown, 1989; Posner, Snyder, & Davidson, 1980; Treisman & Gelade, 1980; van der Heijden, 1992). In neuroanatomical terms, this form of selective attention probably involves regions of the posterior parietal lobe (LaBerge & Buchsbaum, 1990; Petersen,

Robinson, & Morris, 1987). Because the function of this attentional system is to allow for the selection of both locations and objects in the environment, it probably also involves extensive connections with areas in the inferotemporal lobe involved in object recognition (LaBerge, 1995).

Obviously these two classes of attentional function do not function independently. Behavioral goals cannot be accomplished without the ability to efficiently orient to particular aspects of the environment. Moreover, while orienting can at times be "captured" by events in the environment (Yantis, 1993), orienting is typically also goal directed. Despite this interdependence, it is likely that experimental studies that examine selective attention place differential reliance on these two general functions of selective attention.

Measuring Selection: Interference Tasks

A method for examining the operation of selective attention in the laboratory is to create situations in which there are competing sources of information and an individual is to respond to only one information source. A prototypical example of such a situation is the Stroop task (MacLeod, 1991; Stroop, 1935). In the Stroop task, the individual is to name the color in which a word is printed (see Figure 2). The key condition is the situation where the word names a color (e.g., BLUE) that is different from the color in which the word is printed (e.g., red). The conflict between the relevant color and the irrelevant word, results in people being slowed to name the color in this condition compared to when the word is unrelated to any colors (e.g., deep).

This task has been the focus of an enormous amount of research (for review, see MacLeod, 1991). At present, there appear to be at least two aspects of this task that make the Stroop interference effect particularly robust. First, word reading is highly automatized while processing and retrieving the appropriate color name is considerably less automatized. Second, the two dimensions are not equally related to the type of the response because the response that an individual must make is a word that names a color. Exactly this type of information is available in the word dimension while the color information must be translated into a word response (Phaf, Van der Heijden, & Hudson, 1990; Virzi & Egeth, 1985). Both of these characteristics contribute to the Stroop interference effect.

The traditional view of the Stroop task is that it places particular emphasis on function served by regions in the frontal lobe. Individuals suffering from frontal damage are commonly impaired on the Stroop task and imaging studies have shown activation of frontal areas during the performance of this task (Pardo et al., 1990; Bench et al., 1993). There are a number of animal studies suggest that lesions to frontal areas impair performance on conditional tasks (e.g., delayed nonmatching to sample) that seem to place particular emphasis on the ability to use contextual information to guide current actions. In accord with this view, recent theoretical accounts of the Stroop task have focused on the role of representations of the task demands and other contextual information in the efficient control of processing (see Cohen et al., 1990; Kimberg & Farah, 1993).

There are a number of other tasks similar to the Stroop task that have been used to examine aspects of selective attention. One of these tasks is the flanker task (Eriksen & Eriksen, 1974; Eriksen & Shultz, 1979; Miller, 1991; see Figure 3). This task requires individuals to make a simple choice key-press based on the identity of a central letter in a display. For example, individuals may make a one button press when a central letter in a display appears (e.g., H), and make a different button press when another letter appears (e.g., S). In the conflict condition, the display may consist of a central letter requiring one button press and flanking letters corresponding to a different button press (e.g., S S H S S). The conflict between the central letter and the flanking letters slows an individual's response compared to a condition where the flanking letters are mapped onto the same response as the central letter.

The nature of the interference effect in the flanker task also appears to have multiple components. The early account offered by Eriksen and Eriksen focused on the level of response competition. In the original task, there were two letters mapped to each of the two response keys. Thus, it was possible to have the flanking letters different from the target letter but associated with the same response. In this condition, the interference effect is considerably reduced relative to the condition where the flankers are associated with a different response suggesting a response competition component. Furthermore, some studies have found activation of the inappropriate response channel in the incongruent condition using EMG recording methods (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). However, a number of studies have also shown that the visual similarity of the targets and the

flankers is important in modulating the interference effect (e.g., Estes, 1982) suggesting a contribution of basic visual processes involved in segregating the target from the surrounding noise. The importance of location selection in this task suggests a role for posterior parietal networks (LaBerge, 1995; Posner & Petersen, 1990). Like the Stroop task, the flanker paradigm has been used extensively in behavioral and physiological studies of selective attention.

A third variation on the interference paradigm is the local/global task which uses a display where a large letter is made from multiple smaller letters (see Figure 4). The subject's task is to respond to the letter at one level while ignoring the identity of the letters at the other level. Thus, the letter H may be formed from many small S's and the subject's task is to make the button press to the local (small) letter while ignoring the global (large) letter. Navon (1977) showed that there was interference of the global letter identity when individuals were to respond to the identity of the local letter.

The initial observation by Navon (1977) was that there was interference from global information on local judgments but no interference of local information on global judgments. This was taken to indicate that perceptual processing begins with global features and then fills in local details. Unfortunately, it is difficult to distinguish parallel and serial processing (Townsend, 1974; Townsend & Ashby, 1983) and it is possible that processing of local and global information proceeds in parallel but that the global information has a stronger signal or more privileged access to other process resources such as a response selection stage (Hughes, Nozawa, & Kitterle, 1996). Recent studies have qualified the initial finding of interference of global information on local judgments

but not of local information on global judgments. The pattern of performance in this task has turned out to have a number of boundary conditions (Lamb & Robertson, 1990; Robertson, 1996) that determine the actual nature of interference effects. For example, it is possible to arrive at size differences between the local and global figures where the interference pattern reverses to interference of local information on global judgments but not the converse. With respect to the brain areas involved in this task, there are a number of studies that have attempted to relate performance in this task to posterior brain regions. In particular, studies of patients with lesions to the temporo-parietal junction have shown striking deficits in the ability to select one spatial frequency while ignoring the other (Robertson, Lamb, & Knight, 1988; Robertson, Lamb, & Knight, 1991).

The studies using these three tasks to understand aspects of selective attention represent a substantial portion of the research on the behavioral aspects of selective attention. In addition all three of these tasks have been used to some extent to explore neural substrates of attention. In light of the widespread use of these tasks, it is important that we have some understanding of the cognitive operations that these tasks share and the operations that are unique to each. The purpose of the present research is to take one step in that direction by examining the nature of the interference effects that are observed in the performance of these tasks.

In all three of these tasks, when information in the irrelevant dimension is associated with a response that is different from the target dimension, individuals are slower to make a response compared to a neutral condition where the irrelevant dimension is unrelated to any response. In other words, the mean response time (RT) in

the conflict condition is slower than in the neutral condition for all three of these tasks. However, there is evidence that the nature of this interference effect is not the same in two of these three tasks. Detailed analyses of RTs in these tasks have shown subtle differences in performance that are not captured in the traditional analyses of mean RT. Before discussing these results and their theoretical implications in detail, I turn to a discussion of the analytic method that is used to provide a detailed account of RT data in behavioral tasks.

Chapter II : Analyses of RT Distributions

The idea that the nature of cognitive operations can be revealed through the analysis of response times is as old as experimental psychology itself (Donders, 1869/1969; Kulpe, 1909; Ribot, 1899; Sanford, 1888; Wundt, 1907). When a person is required to make a response based on the presentation of some stimulus, we can observe the amount of time that elapses between the presentation of the stimulus and the onset of the individual's response. This total reaction time can be thought of as a composite of the durations of a number of individual cognitive operations (Wundt, 1909) and the original goal was to decompose the composite into the component cognitive operations. This is done by observing the effect that particular experimental manipulations have on reaction time. The original method for achieving this decomposition was the subtraction method of Donders (1869/1969). While there have been subsequent theoretical refinements (McClelland, 1979; Ratcliff, 1978; Sternberg, 1969; Wickelgren, 1977), the notion that response times have something to reveal about cognition remains a central tenet of modern experimental psychology.

The typical approach in studies that use response times as the primary dependent measure is to obtain a number of observations per condition for each individual. The mean response time for each condition for each subject is then computed and, typically, the statistics are done using performance data from a number of individuals. Thus, suppose that 50 observations are collected for each condition and 20 subjects participate in the experiment. The mean RT observed in each condition will be a composite of a total of 1000 observations. One of the benefits of collecting this number of observations

is that it should allow one to obtain a stable estimate of the *true* processing time for that condition in that task. The implicit assumption is that the variability contained in the 1000 observations is error variance. However, all of this variability may not be the result of random error. For example, it is known that manipulations that affect mean RTs also tend to affect the variance of RTs (e.g., Logan, 1988). Thus, experimental manipulations can have effects on RTs beyond simple changes in the mean of the distribution. Moreover, it is possible that characteristics of RTs (e.g., variability) may be affected by experimental manipulations but have no obvious effect on the mean RT. In this light, it seems unlikely that the mean RT contains all that is theoretically meaningful in analyses of speeded performance. If this is not the case, then there may be important aspects of speeded performance that are being missed as a result of cognitive researchers' exclusive use of measures of central tendency. Given the limited number of dependent measures available to cognitive psychologists, we need to exploit the available data for all information regarding underlying cognitive operations. The purpose of the this chapter is to provide some overview of the work that has been done applying more detailed analyses of speeded performance. Current cognitive theories generally make contact with empirical data that is in the form of mean RT. The goal in using more detailed analyses is to bring theories into closer contact with data through the application of more thorough data analytic techniques.

Response Time Decomposition

Implicit (or explicit) in many of the theories surrounding RTs is the notion that the observed RT can be thought of as the sum of the duration of individual cognitive

operations. Some of these durations may not be particularly interesting to a cognitive psychologist. Examples of these might be the time for the peripheral signal to be conducted into the central nervous system and the conduction of a signal to the muscles. Other components are more central to understanding cognition such as discrimination time and the time for response selection (Luce, 1986; Wundt, 1907). If there are more and less interesting components of the total reaction time, it would be helpful if there was a way of separating these components of the response time.

For present purposes, suppose that processing involves successive stages, each of which has some duration. Then it might be possible to think of the total response time as being a sum of multiple independent random variables. In other words:

$$RT = I + C + O \quad (1)$$

where I, C, and O are random variables. Let I represent the time for the stimulus to register on some sensory organ and for the signal to be conducted inwards, and O represent the time for the selected response to be executed by the muscles. Thus, I and O represent the input/output process durations and C represents the time for the execution of central cognitive operations. Revealing the biases of cognitive psychologists, the input/output processes are frequently referred to as the *residual* of the response time. Thus the total RT can be thought of as:

$$RT = C + R \quad (2)$$

We have the sum of two random variables, each with an unknown distribution that yields some observable RT distribution. Obviously the solution for this equation is under-

specified but there are some aspects of the observed RT distribution that might hint at what the component distributions might be.

A method of graphically representing RT performance called a hazard plot provides some insight into components of RT distributions. A hazard plot shows the probability of a response occurring given that one has not already occurred. The general form of hazard plots of response times is of an initial rise and then a later level portion (see Figure 5). The hazard plot of an exponential process is a flat line. The fact that the later portion of RT distributions and exponential distributions share this feature suggests that the empirical RT distribution may have at least one underlying component that is exponentially distributed. If this is correct, there is still the question of how the remaining component is distributed. Moreover, identifying one of these components as having an exponential distribution does not tell us whether this represents the central or peripheral component.

However, suppose that the peripheral component of RTs is made up of a large number of stages that correspond to the conduction of signals in from the periphery and out to the muscles. Further, if the number of such signals is quite large, then one could invoke the central limit theorem and suggest that the residual processing time had a Gaussian distribution. This was the reasoning of Hohle (1965) in suggesting the empirical RT distribution was a convolution of an exponential and a Gaussian distribution, called an ex-Gaussian distribution. In presenting this argument, Hohle identified the central processes as being exponentially distributed and the peripheral processes as normally distributed.

It might not be completely appropriate to use the central limit theorem to solve this problem. For example, Luce (1986) notes that it is not clear that the number of terms entering into this residual is all that large. However, the ex-Gaussian distribution has been very successful in modeling the shapes of RT distributions across a wide variety of experimental situations (Balota & Spieler, 1997; Hockley, 1984; Hohle, 1965; Ratcliff, 1978, 1979; Spieler, Balota, & Faust, 1996). Thus, while the assumptions that led to this distribution may be open to question, we are left with a model that has had remarkable success when applied to the empirical data. Moreover, while there may be a problem with the specific reasoning that Hohle used to arrive at the ex-Gaussian, I will show that the parameters of the ex-Gaussian are differentially sensitive to particular cognitive operations. It is largely due to its potential theoretical import, coupled with its success in modeling the empirical RT distributions that I will be using the ex-Gaussian distribution to explore the effect that conflict in selective attention tasks has on the shapes of RT distributions.

The shape of the ex-Gaussian is captured in the three parameters, Mu, Sigma, and Tau. The Gaussian component to the ex-Gaussian contributes two parameters, Mu, reflecting the modal portion of the distribution, and Sigma, reflecting the symmetric variability about the mode. The exponential parameter, Tau, corresponds to both the mean and the standard deviation of the exponential distribution. In the ex-Gaussian distribution, this parameter primarily reflects the slow tail of the distribution. The mean of the ex-Gaussian distribution is simply the sum of the mean of the Gaussian and the mean of the exponential, Mu plus Tau. Thus, changes in the mean of the distribution can

occur from changes in the Gaussian component, the exponential component, or some mixture of the two. In Figure 6, four distributions are pictured that show how changes in the parameters of the ex-Gaussian affect the overall shape of the RT distribution. As shown, a change in Mu acts to shift the distribution. A change in Sigma leaves the central tendency of the distribution unchanged but increases its spread. Finally a change in Tau results in an increase in the skewing of the distribution.

A demonstration of the utility of distributional analyses in general, and the ex-Gaussian distribution in particular, is a study that showed that the Gaussian and exponential components of the RT distribution could be differentially influenced in different tasks (Hockley, 1984). Mean response time in both memory scanning and visual search tasks increases as the size of the search set increases. As noted above, such changes in mean RT can occur from changes in the Gaussian or in the exponential portion of the distribution. Utilizing the ex-Gaussian analysis, Hockley showed that the increase in mean RT with increasing set size in memory scanning was almost entirely reflected in the increase in the Tau parameter. In contrast, the increase in mean RT with increasing set size in visual search was almost entirely reflected in the Mu parameter (see Figure 7). Thus, across these two tasks, there was dissociation between the Gaussian and exponential components of the distribution. These results are important because they suggest that manipulations that affect mean RT result in changes in the underlying RT distribution can be task specific. Moreover, this task specificity is not necessarily apparent in an analysis restricted to only mean RT.

The results by Hockley also provide some support for Hohle's idea that the parameters of the ex-Gaussian may reflect different cognitive processes. Performance in the memory scanning task is dependent on the ability to maintain the search set in memory and conduct multiple comparisons between the target and the members of the search set. On the other hand, the visual search task places a greater emphasis on the extraction of information from the environment. Thus, these tasks appear to rely more on central and peripheral processes respectively. However, there is a caveat that should be mentioned regarding this interpretation. This interpretation is mainly consistent with the considerably weaker claim that the parameters of the ex-Gaussian are differentially sensitive to particular types of cognitive operations, not the original claim made by Hohle that there is a one to one correspondence between cognitive processes and the parameters of the ex-Gaussian.

In general, there are two stances that one can take when applying the ex-Gaussian distribution to empirical data. First, one can accept general theoretical assumptions that lead to the ex-Gaussian, with an exponential central component and a Gaussian residual component. Or one can take the view that, for whatever reason, the ex-Gaussian distribution seems to do a very good job of fitting empirical distributions and that it is best viewed as a useful tool for capturing changes in the RT distribution in response to experimental manipulations. The view I take in the present paper is a mixture of the two. I will argue that the ex-Gaussian frequently divvies up the RT distribution into theoretically meaningful components, as indicated by the selective influences of experimental manipulations on each of the ex-Gaussian parameters. However, it is also

unlikely that one can establish a one to one mapping of processes or sets of processes to components of the distribution that will hold across a wide variety of experimental situations. Thus, it is crucial to devote considerable thought to the analysis of the task and its component processes.

It is worth emphasizing a practical advantage to the ex-Gaussian that complements its theoretical utility. The ex-Gaussian has the advantage of simplicity and some intuitive appeal. In contrast to other families of distributions, it has few parameters (three), which correspond to theoretically interesting components of the distribution (mode, symmetric variability, skew). Moreover, it is fairly easy to understand how the changes in the parameters result in changes in the overall shape of the RT distribution. This greatly eases the interpretation of the experiments using this distributional model. The relative simplicity of the ex-Gaussian in combination with its success in fitting RT distributions across a variety of situations makes it ideally suited as a tool for investigating the effect that experimental manipulations have on the shapes of RT distributions.

Chapter III: Application of Distributional Analyses to Selective Attention tasks

The primary focus of the present research is to use the ex-Gaussian distribution to examine the nature of interference effects in a number of traditional selective attention tasks. In the three tasks that I have discussed, Stroop, local/global, and flanker tasks, individuals have to select among competing sources of information. This competition results in a slowing of performance. The question that the distributional analysis addresses is how the underlying RT distribution reflects this slowing of mean RT. As I mentioned earlier, an increase in mean RT could be a reflection of the entire distribution shifting, which would be reflected by a change in the Mu parameter of the ex-Gaussian. On the other hand, the increase in mean RT could be a result of the tail of the distribution being pulled out, resulting in a more skewed distribution (Figure 6). Such a change would be reflected in the Tau component of the ex-Gaussian.

Applying the ex-Gaussian analysis to the Stroop task, Heathcote et al. (1991) found that the interference effect (evidenced in mean RT) was present in both the Mu and the Tau components. The interference effect in Mu was approximately 60 ms while the interference effect in Tau was approximately 40 ms (estimated from Heathcote et al., Figure 1, pg. 343). This pattern of interference in both Mu and Tau has been replicated several times in this laboratory (Spieler et al. 1996, for example, see Figure 8). This indicates that the slowing of mean RT that occurs when the color and word conflict is a reflection of a distribution that is both shifted and more skewed.

A second interesting aspect of the ex-Gaussian analysis of Stroop performance is the finding that in the congruent condition, the effects in Mu and Tau move in opposite

directions (see Figure 8). When the word and the color information matches, there is facilitation that shifts the distribution (reflected by the Mu parameter) but interference in the tail of the distribution (reflected by the Tau parameter). Interestingly, in the literature on the Stroop task, it is not uncommon for there to be failures to find reliable facilitation in the congruent condition relative to the neutral condition (MacLeod, 1991). Based on the distributional analysis, this is probably due to the mixture of facilitation in Mu and interference in Tau. Because the mean RT is simply Mu plus Tau, effects that are in the opposite direction in these two parameters will tend to offset each other. Thus, in this case, the distributional analysis has not only provided more detailed information about the nature of effects that have already been identified in mean RT, but it has also revealed effects that have been overlooked because mean RT has been the sole dependent measure.

Analyses of RT distributions in the Stroop task have indicated that age may be a factor that has a selective influence on components of the RT distribution (Balota, Spieler, & Faust, 1994; Spieler, Balota, & Faust, 1996). Older adults commonly show a Stroop interference effect in mean RT that is larger, both in absolute terms, and proportionately, than younger adults (Comalli, Wapner, & Werner, 1962; Spieler et al., 1996), indicating age-related deficits in some attentional selection processes. The application of the ex-Gaussian analysis to Stroop performance in younger and older adults revealed that the interference effect in Mu was very similar for these two groups. However, the interference in the Tau parameter was twice as large for older adults as younger adults. Thus, the group differences observed in mean RT can be attributed to

differences in only one component of the RT distribution (see also Balota & Spieler, 1997).

Central to the purposes of this dissertation, there is evidence that the nature of interference effects is different across selective attention tasks. Heathcote et al has also shown that while conflict in the Stroop task shifts and pulls out the tail of the RT distribution, conflict in the local/global task results in effects in Mu only, and no effects in Tau. These results indicate that the parameters of the ex-Gaussian can reveal task dependent changes in the nature of RT distributions. This is consistent with the observation of Hockley (1984) who showed that different tasks have different influences on the parameters of the ex-Gaussian distribution. To the extent that these are consistent and replicable task differences, then these are patterns for which theories will ultimately need to account.

In sum, there are three empirical observations that highlight the utility of ex-Gaussian distribution analyses. First, analyses of the Stroop task revealed that the Stroop effect in mean RT is a reflection of an underlying distribution that is shifted and becomes more skewed in response to conflict between the color and word dimensions. Second, factors that influence the size of the interference effect in mean RT may do so by selectively influencing only one component of the RT distribution (Balota & Spieler, 1997; Spieler et al., 1996). Third, there appears to be task specificity in the manner in which the interference effects observed in mean RT are reflected in the underlying RT distribution (Heathcote et al.).

Preliminary Experiments

Before pursuing the possible theoretical implications of these results, I review two studies that replicate and extend the findings of Heathcote et al. showing differences between interference effects in Stroop and local/global tasks. As noted earlier, the pattern of the parameters in the Stroop task has been replicated in a number of studies (e.g., Spieler, et al.). With respect to the local/global task, there is only the single reported experiment by Heathcote et al. The purpose of the analyses of the first study was to replicate the basic pattern of interference effects in the parameters of the ex-Gaussian distribution in the local/global task. In this light, I reanalyzed data obtained from a battery of cognitive tasks collected on younger and older adults, and individuals with dementia of Alzheimer's type (the present analyses examine only the data from the younger and older adults). In light of the results from the Stroop task indicating that age may have a selective influence on components of the RT distribution, both younger and older adults were included to determine if this selective influence is general across tasks or if age effects might also be task dependent.

Shown in Figure 4 are examples of stimuli from the congruent, neutral, and incongruent conditions in the present local/global task. Participants received two blocks of trials. In one block of trials individuals responded to the local dimension of the stimulus while in the other block they responded to the global dimension. There were a total of 64 observations per cell. There was no interference or facilitation when individuals responded to the local dimension, there appeared to be robust interference and facilitation for global responses and this is shown in Figure 9. As noted previously, the

exact pattern of interference and facilitation depends on a number of characteristics of the display. The fact that there was an effect on global responses from local information suggests that the local information was more discriminable in this study.

The results of fitting the ex-Gaussian to the data from the local/global task are shown in Figure 10. Note that for global responses, there are clear interference and facilitation effects in Mu, but absolutely no effects in Tau. Moreover, there was no evidence for age differences in the pattern of Mu or Tau estimates as was found in the Stroop task ($p > .10$).

These results replicate the observation made by Mewhort et al. (1992). Specifically, the effect of interference in the local/global task is evidenced as a shift in the entire distribution. Thus, these results along with those of Mewhort et al. stand in contrast to the results from the Stroop task in which interference both shifted and magnified the tail of the distribution. These results are important because they demonstrate the replicability of the task differences in the analyses of RT distributions.

The two tasks that we have considered so far differ along a number of dimensions, each of which may be important in determining how interference is reflected in the underlying RT distribution. The clearest difference between these two tasks is in the relation between the relevant and irrelevant dimensions. In the local/global task, the irrelevant dimension is present in another spatial frequency. Thus, the process of selection requires the enhancement of visual processing for the relevant frequency and the suppression of processing at the irrelevant frequency. In contrast, selection in the Stroop task requires one to select and respond based on an attribute of a single, spatially

integrated object. It is possible that selection based on spatial information may have temporal characteristics that are different from other forms of selection. For example, a number of theorists have suggested that spatial information plays a privileged role in the context of selective attention (LaBerge & Brown, 1989; Nissen, 1985; Schneider, 1993; 1995; van der Heijden, 1992). From the present results, it appears that when selection is between competing sources of information that can be distinguished based on spatial information, interference is more likely to take the form of a simple shift of the distribution. On the other hand, when selection is between competing information that cannot be separated based on spatial information, then interference may be more likely to result in a distortion of the actual shape of the RT distribution.

The distinction between spatial and nonspatial selection suggests an account for age effects. Recall that there was a large age difference found in the Stroop interference effect and this age difference was due entirely to an increase in the Tau component. In the local/global task, minimal age differences were found and there was no indication that any age differences were strongly localized in one parameter of the distribution. If the difference between these tasks lies in spatial/nonspatial dimension, then this is consistent with the notion that older adults may be less impaired in spatial selection than in other forms of selection (e.g., Connelly & Hasher, 1993; Hartley, 1993).

If the spatial component to these tasks is important in determining the nature of interference effects, then this leads to an interesting prediction for another selective attention task. The flanker task (Eriksen & Eriksen, 1974) requires individuals to make a button press in response to a centrally presented letter. In the conflict condition, there are

letters flanking the target letter that are associated with the opposite response (see Figure 3 for examples). In this task, selection may be accomplished by selecting the target location and filtering out the irrelevant locations. If the effect that interference has on the shape of the underlying RT distribution is influenced by whether or not spatial selection can be used, the interference effects in the flanker task should be similar to those in the local/global task because both tasks require the selection of spatial information. Furthermore, if older adults are less impaired on tasks that require spatial selection as opposed to other forms of selection, then this task should also show similar patterns of performance in younger and older adults both in mean RT and in the parameters of the distributions. To test this possibility, I analyzed the results from a flanker task that were included in the same cognitive test battery as the local/global task. Again, the analyses included both younger and older adults.

The mean RT results for this experiment are shown in Figure 11. Analyses on these data revealed reliable interference and facilitation effects but no age differences in interference or facilitation. The results of the ex-Gaussian analyses are shown in Figure 12. Note that while the Mu parameter shows robust interference and facilitation effects, the pattern of interference and facilitation appears to be quite different in the Tau parameter estimates. It appears that if there is any effect of Condition on the Tau parameter estimates, it is in the opposite direction as that observed in Mu. Indeed, analyses of the Mu parameter estimates showed clear interference and facilitation effects in Mu. Interestingly, there was also a reliable effect of flanker congruency on Tau but the effect was in the opposite direction as that in Mu. Because the mean RT is Mu plus Tau,

the interference effect in the flanker task appears to be quite large in the modal portion of the distribution but this effect is partially offset by a decrease in the Tau estimates. In line with the results from the local/global task, analyses showed reliable overall differences between younger and older adults in both Mu and Tau, but clearly there was no hint of an Age by Condition interaction in either of these two parameters.

The results from these two experiments suggest that, in contrast to the robust interference effects observed in the Tau parameter in the Stroop task, both the local/global task and the flanker task show either no interference effect in Tau (local/global task), or a reversal of the pattern observed in the Mu estimates (flanker task). This can be taken as tentative support for the idea that these tasks may be tapping different selection processes. It may be the case that when selection operates within a particular processing domain such as spatial location, interference effects are almost totally in the Gaussian component of the RT distribution. When a more complex form of selection is required as in the Stroop task, the result is interference effects that are also in the Tau component. In the next chapter I will explore in more detail possible accounts for these task differences.

Chapter IV: Preliminary Theoretical Account

The goal of this chapter is to provide some theoretical framework for interpreting this pattern of interference effects described so far. In the discussion of the ex-Gaussian distribution, I left open the possibility that the parameters may be differentially sensitive to certain types of cognitive operations. Following Hohle (1965), I suggested that Tau may be more sensitive than Mu to manipulations affecting the operation of central cognitive processes. However, what constituted central processing was left undefined. In light of the task differences discussed so far, it might be possible to define ‘central’ operations within the context of the present selective attention tasks. To do so, I first review the evidence from the neuropsychological literature suggesting that the locus of attentional selection in these tasks differs. Following this, I discuss a particular class of models of response times that provide some additional information regarding task differences in the interference effects. Finally, I present an overview of four additional experiments that provide further insight into the linkage between cognitive operations and the resulting effects in RT distributions.

Evidence for Different Selective Operations

As I discussed in Chapter 1, the Stroop task has long been viewed as a “frontal” task (see Stuss & Benson, 1984 for review). While it is certainly the case that performance on this task requires extensive use of a number of distributed brain regions, the fact remains that the Stroop task performance is often seriously impaired in individuals with damage to frontal regions. The evidence that is available from the

imaging literature is, to some extent, consistent with the involvement of frontal areas.

Both of the available studies using positron emission tomography have found activation in anterior cingulate gyrus (e.g., Bench, et al, 1993; Pardo, et al, 1990). The cingulate gyrus is connected with multiple other areas in the frontal lobe whose functioning is likely to be compromised in patients with frontal lesions (e.g., Passingham, 1993).

While lesions to the frontal lobe areas commonly result in deficits in Stroop performance, lesions to inferior parietal areas are likely to result in deficits in selective attending to local or global features (Robertson et al., 1988, 1991). It is clear that the posterior parietal cortex plays some role in the selection of particular locations in the environment (Bushnell, Goldberg, & Robinson, 1981). Specifically , evidence suggests that selection for particular locations or particular spatial frequencies appears to be accomplished through networks in the posterior parietal region and inferotemporal object recognition areas that interact via the thalamus (e.g., see LaBerge, 1995). However, the specifics of the neural structures crucial to the performance in each of these tasks is unknown. The important point is that there is good evidence for suggesting that the particular neural structures that mediate selection in the present selection tasks are different. Such evidence supports the notion that there might be differences in the processing dynamics that could be revealed through analyses of RT distributions. There is a particular class of models of response times reinforce the notion that there are fundamental computational differences between processes that result in changes primarily in Mu and processes that result in changes primarily in Tau.

Diffusion Processes

Random walk and diffusion models represent a class of quantitative models that have been applied extensively to the modeling of RT data (Ratcliff, 1978; Ratcliff & Spieler, 1997; Strayer & Kramer, 1994; Ward & McClelland, 1989)¹. In these models, information processing is viewed as an iterative process of sampling (e.g., from sensory channels, memory, and other information sources). Each sampling provides some evidence for one of the possible responses. As shown in Figure 13, each piece of evidence compatible with a particular response results in a move one closer to the response criterion, and each piece of evidence for the other response results in a move further from the criterion. Approaching a particular response criterion is a function of the *difference* in strength of evidence for and against that response. Over time, sufficient information accumulates for one response and that response is made, yielding a response time. When information accrual is continuous, the rate of approach to the particular response criterion is called the drift rate. Fast responses are the result of fast information accrual and hence, a fast drift rate. Conversely, slow responses result from a slow rate of information accrual which is modeled by a slower drift rate. Across multiple trials, the same response yields a distribution of response times because the drift rate is a random variable that varies from trial to trial.

The general distributional characteristics of diffusion processes are fairly well known (e.g., Ratcliff, 1978; Ratcliff & Van Zandt, 1996; Usher & McClelland, 1996). The effect of experimental manipulations can be modeled as a change in either the mean

drift rate or the response criterion. If we consider a manipulation that slows the drift rate, the result is to increase mean RT and to change the RT distribution in a particular manner. Specifically, the increase in mean RT occurs as a result of a shift and an increase in the skewness of the distribution. Shown in Figure 14 are the changes in the parameters of the ex-Gaussian fit to the resulting simulated RTs as a function of changes in the drift rate of the diffusion process.

If competition in the Stroop task changes the drift rate, then the effect on mean RT and on the shape of the RT distribution would be quite similar to that observed by Spieler et al. Thus, processing in the Stroop task appears to be well modeled as a diffusion process. In contrast, this general tendency for Mu and Tau to be closely tied in the diffusion model makes it difficult for the model to parsimoniously reflect the effects observed in the flanker and local/global tasks. It would require fairly complex set of changes in multiple parameters of a diffusion model before one could obtain the shifts of the distribution without corresponding change in the tail of the distribution such as was observed in the local/global task. Thus, one step toward refining the notion of central and peripheral processes is that central processes are well conceptualized as a diffusion process while this is not the case of manipulations that influence processes relatively early in the information processing stream. Interestingly, the diffusion model has typically been termed a “decision” model. Thus there is some consistency here with Hohle’s suggestion that central, decision processes are reflected by the exponential component of the ex-Gaussian.

The preceding discussion suggests that when relevant and irrelevant information can be separated based on spatial information, the effect of irrelevant information is reflected primarily in the Mu parameter of the ex-Gaussian. If such a separation cannot be made based on spatial information, later selection operations must be brought to bear. Processing at this later stage might be better conceptualized as continuous accrual of information, and hence, better modeled as a diffusion process. In this case, the effect of irrelevant information is reflected in changes on both Mu and Tau components.

Age Effects at Different Levels of Selection

An additional source of evidence that the attentional operations involved in these tasks differ is the finding that age differences are not equivalent across the Stroop, flanker and local/global tasks. Recall that Spieler et al. reported that the interference effect in the Stroop task was disproportionately larger in older adults compared to younger adults. Moreover, this increase in interference was due to an increase in the tail of the RT distribution, as shown by the Tau estimates. This result contrasts with the results from the flanker and local/global task in which age differences were quite small. The magnification of the Stroop effects in Tau in older adults is consistent with a localized age-related deficit in a selection process that is later, more central, and perhaps involving functions subserved by frontal brain areas.

I am not the first to suggest that aging may impact central processing to a greater extent than less central processes or that aging has a large impact on performance on tasks that place particular reliance on the functions attributed to frontal brain regions. Evidence from traditional neuropsychological studies (Moscovitch & Winocur, 1992) and

neuropathological markers (Morris, Storandt, McKeel, et al., 1996) is consistent with the notion that aging results in a significant decrement in the efficiency of frontally mediated processing. The prediction from the results that I have discussed so far is that tasks that result in changes in the RT distribution such as that observed in the Stroop task, should be the tasks that also exhibit the disproportionate age differences. Moreover, these age differences should be localized primarily in the tail of the RT distribution.

Generalized Slowing and Distributional Analyses

The notion that the comparison of the RT distributions of younger and older adults reveals the impact of aging on specific processes is not entirely consistent with some analyses of age differences in speed performance measures (Cerella, 1985; 1990; 1994; Myerson, Hale, Wagstaff, Poon, & Smith, 1990). One prominent theoretical position in cognitive aging is that it is possible to characterize age differences in speeded performance using a limited number of “general” slowing factors. A general slowing factor represents the degree to which processing is slowed in older adults relative to younger adults across a large range of tasks.

The general slowing account of the cognitive effects of aging is motivated by the observation that, across a wide variety of tasks, it is possible to capture the nature of speeded performance in older adults as a simple multiplicative function of the response latencies for younger adults. The empirical observation that there is a strong relationship between the mean response latencies of younger adults and those of older adults is not controversial. However, there is considerable disagreement about what theoretical conclusions can be drawn from this observation (e.g., Cerella, 1994; Myerson Wagstaff,

& Hale, 1994; Perfect, 1994; Ratcliff & Spieler, 1997). One position is that the effect of aging is to slow some general speed-of-processing factor and the influence of this global change is evidenced in a wide variety of situations. If the multiplicative relationship observed at the level of mean RT is a reflection of such a relationship at the level of individual RTs, the response time distributions of older adults should have the same shape as that of younger adults, simply shifted up the RT scale and stretched out. Thus, the considerably larger age differences in interference in Tau than in Mu as seen in Spieler et al. (see also Balota & Spieler, 1996) is inconsistent with a simple general slowing prediction.

The modeling RT distributions provides an accurate method for comparing the RT distributions in younger and older adults. In a number of experiments, this method has revealed process specific age differences that, in some cases, would not have been captured if the analysis had only been conducted at the level of mean RT (e.g., Balota, Spieler, & Faust 1996; Spieler, et al., 1996; Spieler & Balota, 1996). The experiments reviewed so far suggest that a simple general slowing account is not adequate to account for age differences in RT distributions. Instead, the results so far suggest that older adults may suffer from a deficit in particular selection processes. The following experiments will include both younger and older adults with the goal of both providing additional insight into how age influences components of RT distributions in general and the nature of age differences in levels of selective attention specifically.

Chapter V: Experiments

The problem with the present between-task comparisons is that these tasks differ along a number of dimensions aside from whether or not selection can be based on spatial information. The following experiments help to clarify what factors result in effects only in Mu versus effects in both Mu and Tau. For the following experiments, a premium is placed on replicating previous results. There are relatively few studies that have taken the approach of modeling RT distributions, and even fewer have taken the approach of modeling distributions in selective attention tasks. Thus it is important to demonstrate that the reviewed findings are robust and replicable. The current experiments also evaluate two possible accounts for the interference effects in Tau and extend the analyses of RT distributions to two additional selection tasks.

In the next section, I provide an overview of each of the experiments and the predictions concerning how interference in each experiment might influence the shape of RT distributions.

Flanker Variations

The first two experiments are variations of the flanker task. These experiments were intended to replicate the findings from the first flanker experiment and to extend the paradigm to examine a possible account for interference effects in Tau found in the Stroop task.

In the results of the first flanker task that I reported in Chapter 3, there was one characteristic of this study that made it different from other flanker tasks that have been reported in the literature (e.g., Eriksen & Eriksen, 1974). Specifically, there was only one

letter associated with each of the two responses. Previous studies have typically used at least two letters associated with each response. By pairing two letters to each response, this adds an additional factor to the design, i.e., compatibility. On some trials, a participant might be presented with flanking letters that are different from the target but are associated with the same response (compatible) while on other trials the flanking letters are associated with a different response (incompatible). Thus, compatibility becomes an additional factor in the design. Experiment 1 uses two letters for each of two responses, thereby increasing comparability to other experiments in the literature. It should also be noted that there is some evidence that as stimulus-set decreases, individuals may adopt strategies that can modulate the interference and facilitation effects (Logan, Zbrodoff, & Williamson, 1984). Thus, Experiment 1 reduces the likelihood that individuals might engage in strategies that could complicate the interpretation of the results. Finally, Experiment 1 provides an opportunity to replicate the original flanker results reported in Chapter 3.

Experiment 2 examines a possible account for the interference effects in Tau found in the Stroop task. One of the most salient characteristics of the Stroop task is the asymmetry in stimulus to response association for the color and word dimensions. The word has a stronger relation with the required verbal response than does the color. In the local/global and flanker tasks, subjects are given an stimulus-to-response (SR) mapping where letters are mapped to arbitrary button presses. The strength of connection between the letters and the response is defined only within the context of the experiment. Thus,

the target and distracting information is more closely balanced in SR strength in the typical flanker task compared to the Stroop task.

To examine the possibility that the asymmetry in SR strength might contribute to the interference effects in Tau, Experiment 2 used stimuli that differed in SR mapping strength. The manipulation of strength is accomplished in the context of a flanker task. This experiment used words that directly specify the response (LEFT, RIGHT) or are arbitrarily mapped to a particular response (LARGE, SMALL). The prediction is that when a strong response-related word appears as a flanker and a weak response-related word appears as a target, that interference will be greater than when the targets and flankers are more equally matched. Indeed, the condition where the weak target is flanked by strong flankers is comparable to the Stroop task. The question is whether interference in this situation is found in Tau. If the strength of the competing dimension is the cause of interference effects in Tau, then the increased interference observed in this flanker task will also be reflected in the Tau parameter of the ex-Gaussian. On the other hand, if the nature of the interference effects are determined by whether the two competing dimensions can be separated based on spatial information, then the pattern of interference in this task should be the same as the previously reported flanker results (i.e., primarily a change in Mu).

Experiment 2 also addresses a central issue regarding age differences in speeded performance in general and selective attention in particular. First, as discussed earlier, slowing accounts of age-related changes in cognition suggest that aging results in a slowing of information processing rate in such a manner as to leave the qualitative nature

of processing unaffected. This view predicts that overall age differences should occur in all three parameters of the ex-Gaussian and that the interference effects should also be similar. On the other hand, there are studies that suggest that age differences tend to be larger in the Tau parameter. The present study further tests the predictions of a general slowing model by looking at RT distributions in younger and older adults.

Additional Selection Tasks

In Experiments 3 and 4, the analyses of RT distributions are extended to two additional selection tasks with the goal of further evaluating the spatial/nonspatial distinction as an account for the different effects of interference on components of RT distributions.

Experiment 3 examines RT distributions in a spatial variant of the Stroop task. Specifically, this experiment addresses a situation where the color and word information are spatially separated. In this variation of the Stroop task, individuals can select the relevant dimension of the display using spatial location. If competition in spatial selection results in effects only in Mu, then the results from this task should be similar to those from the flanker and local/global tasks. In other words, the interference effect should be reflected primarily in the Mu parameter of the ex-Gaussian. Because previous studies have suggested that there are smaller age differences in tasks requiring spatial selection (see Hartley, 1994 for review), separating the color and word dimensions should reduce or eliminate age differences in Stroop performance.

Experiment 4 examines the effect of interference in the Simon task. In the typical Simon task, individuals are required to make a button-press response based on the

identity of a stimulus (e.g., LEFT, RIGHT) that is presented either to the left or the right of a central fixation. When the location of the stimulus relative to the fixation conflicts with the required response (LEFT on the right), individuals are slower to respond compared to when the location and response match (LEFT on the left). The original account for this effect was that individuals are biased to respond in the direction of stimulation (Simon, 1969). More recent research indicates that the locus of the effect is at response selection and execution (Lu & Proctor, 1995). The onset of a stimulus in a particular spatial location results in partial activation of an associated spatial code that is used to select the response (Umiltà, 1995). The response locus of the effect is supported by research using lateralized readiness potentials (LRP). These are evoked brain potentials that appear over motor cortex, and are largest contralateral to the side that a response is made. Studies have shown that an LRP can be evoked on the left side by the onset of a stimulus on the right (Osman, Moore, & Ulrich, 1995). More important, this occurs independent of the identity of the stimulus.

The previous results suggest that interference in spatial selection results in shifts of the distribution while interference in nonspatial selection results in both a shift and an increase in the skewing of the distribution. From this perspective, when the relevant and irrelevant dimensions of a display are integrated, interference should be evidenced in both Mu and Tau. In the Simon task, the spatial information is an attribute of the stimulus to which a response must be made. This feature makes the Simon task similar to the Stroop task where the distracting word information is an attribute of the selected letter string. Thus, one might expect that the interference effect in the Simon task should be observed

in the Tau component and not just in the Mu component of the ex-Gaussian. Moreover, if one finds this pattern, then based on the present arguments, one might expect older adults to have more difficulty in the Simon task than in the previous spatial selection tasks. In addition, the age differences should occur in the Tau component of the distribution.

However, there is an alternative set of predictions regarding the Simon task. Specifically, the general starting point for this research was the suggestion by Hohle (1965) that central cognitive (or decision) operations are reflected by the exponential component, while more peripheral operations are reflected by the Gaussian component. The studies that have shown interference only in Mu have emphasized competition that occurs relatively early in processing, namely at the level of spatial selection. However, the distinction between peripheral and central processes made by Hohle, and generally supported by the experiments reviewed above, predicts that interference at the response level might also be reflected in the Gaussian component. This might also suggest that, if age differences are driven primarily by those cognitive operations that are reflected in the exponential component of the distribution, then age differences in this task should be small. Older adults should not show disproportionate interference effects in the Simon task and the effects in each of the parameters of the ex-Gaussian should be similar in young and old.

Experiment 1

The first experiment is a replication of the flanker experiment presented in Chapter 3. Recall that the first flanker experiment had only two stimuli in the response set. Previous experiments have typically included a larger stimulus set. Thus, to increase comparability with other experiments in the literature, the present experiment expands the size of the stimulus set.

Method

Participants

Twenty younger adults were recruited from the undergraduate student population at Washington University. Participants were 19 to 22 years old ($M = 19.5$, $SD = 1.4$) and had 13 to 17 years of education ($M = 14.2$, $SD = 1.2$). Individuals participated for course credit.

Apparatus

Stimuli were presented on a 14 inch Color VGA monitor interfaced with a IBM compatible computer. A standard keyboard was used to collect responses and to measure response latency to the nearest *ms*. Individuals made their response by pressing the Z and / key on the keyboard. These keys were raised in height slightly above the other keys on the keyboard.

Stimuli and Design

Letters were written in a Courier font with 8 by 8 pixel letters. Each letter subtends approximately .3 degree of visual angle. The letters were C, S, H, K, and Y. All letters were displayed in upper case in white on a black background. The letters were

divided into two pairs (C and S, H and K) where one pair was assigned to the left response key and the other assigned to the right response key. The letter Y served as the neutral flanker and it was not associated with any response.

There are two factors that describe the relation between targets and flankers. First, there is the congruency of the targets and flankers. This refers to whether the targets and flankers are the same (congruent) or not (incongruent). Second, there is the compatibility of the targets and flankers. The targets and flankers may be associated with the same response (compatible) or the opposite response (incompatible). Thus, there are three conditions in the traditional flanker task, congruent-compatible, incongruent-compatible, and incongruent-incompatible that are compared to the neutral condition. The neutral condition consisted of flankers that were not associated with any response. In total there were 32 practice trials and 768 trials in the experiment.

Procedure

At the beginning of the experiment, participants were given the instructions which included the key mapping (e.g., C and S mapped to the left key; H and K mapped to the right key or vice versa). Individuals were told to make their responses as quickly and as accurately as possible.

On each trial, the following sequence of events occurred: a) a single plus sign appeared in the center of the screen for 500 ms b) the screen was blank for 200 ms, c) three letters appeared, the target letter in the position of the plus sign and the flanking letters appearing offset by 8 pixels from the target letter (approximately .3 degrees), and the letters remained on the screen until the participant responded or until 2500 ms had

elapsed, d) the screen cleared once a response was made, e) a 1000 ms intertrial interval was initiated before the start of the next trial. In the event of an error, which was defined as an incorrect button press or 2500 ms elapsing before the response was made, there was a 700 Hz tone presented for 500 ms and the message “*** Error ***” was displayed in the center of the screen for 1000 ms.

Thirty two practice trials appeared at the beginning of the session. The sequence of events for each trial was exactly the same as in the experimental portion. Breaks were provided every 100 trials. Feedback in the form of speed and accuracy information was given after every block of trials. The entire experimental session lasted approximately 45 minutes.

Results

The response times for those trials where the individual pressed the incorrect button were eliminated from all RT analyses. In addition, RTs that fell below 200 ms or 3 standard deviations below the condition mean or greater than 2000 ms or 3 standard deviations above the condition mean were eliminated from all RT analyses. Using these criteria, 1.65% of responses were eliminated from the analyses. An analysis on the proportion of data trimmed as a function of condition did not suggest any differential trimming of data across condition ($p > .10$).

Mean RT Analyses

As shown in Figure 15, the mean RT results revealed the expected ordering of conditions. Indeed there was a reliable effect of condition, $F(3, 57) = 74.97$, $MSE = 62$, $p < .001$. Relative to the neutral condition, the incongruent-incompatible condition showed

reliable interference, $F(1, 19) = 123.98$, $MSE = 45$, $p < .001$; and the congruent-compatible condition showed reliable facilitation, $F(1, 19) = 22.45$, $MSE = 70$, $p < .001$. The incongruent compatible condition did not differ from the neutral condition ($F < 1$).

Error Analyses

As shown in Figure 15, the ordering of conditions in error rate generally paralleled the results found in the RT analyses, with a reliable effect of condition $F(3, 57) = 20.22$, $MSE = .0003$, $p < .001$. Relative to the neutral condition, participants made fewer errors in the incongruent-compatible condition, $F(1, 19) = 9.82$, $MSE = .0001$, $p < .01$, and more errors in the incongruent-incompatible condition, $F(1, 19) = 27.87$, $MSE = .0003$, $p < .001$. The congruent-compatible condition did not differ reliably from the neutral condition, $F(1, 19) = 1.45$, $MSE = .0001$, $p = .25$.

Ex-Gaussian Analyses

Turning to the ex-Gaussian analyses, the ex-Gaussian was fit to each of the four conditions for each subject. Thus, there was a total of 80 distributions fit in this analysis. Goodness of fit was computed for each distribution using a chi-square statistic. Significant chi-square values suggest that the empirical distribution deviates significantly from the ex-Gaussian. Three of the eighty distributions resulted in chi-square values that were significant at the .01 level. However, each of these three values were very close to the critical value and the fits even for these distributions were quite good. Analyses were done on the parameter values both with and without these distributions and the results were qualitatively identical. The following results are for analyses that included these distributions. As shown in Figure 16, the results are straightforward. There was a

reliable effect of condition on Mu, $F(3, 57) = 32.73$, $MSE = 101$, $p < .001$. Paralleling the results in the mean RT analyses, there was interference in the incongruent-incompatible condition, $F(1, 19) = 33.42$, $MSE = 140$, $p < .001$, and facilitation in the congruent-compatible condition, $F(1, 19) = 5.16$, $MSE = 148$, $p < .05$, while the incongruent-compatible condition did not differ from the neutral condition ($F < 1$). For Sigma, there was a reliable main effect of condition, $F(3, 57) = 16.26$, $MSE = 43$, $p < .001$. The effects in Sigma followed those found in Mu, namely there was interference in the incongruent-incompatible condition, $F(1, 19) = 17.57$, $MSE = 46$, $p < .001$, and facilitation in the congruent-compatible condition, $F(1, 19) = 4.87$, $MSE = 51$, $p < .05$, while the incongruent-compatible condition did not differ from the neutral condition ($F < 1$). In contrast, there was no effect of condition in Tau, $F(3, 57) = 1.31$, $MSE = 103$, $p = .28$.

Discussion

The results of Experiment 1 replicate the general pattern of results observed in the first flanker experiment reported in Chapter 3. In light of the small number of studies that have examined RT distributions in selective attention tasks, it is important to replicate basic phenomena the results of Experiment 1 do just that. However, there is one important discrepancy between the present results and the previous results. In the original flanker experiment, recall that the effects in Mu and in Tau were in the opposite directions. Because the only change between Experiment 1 and the previous experiment is in the number of items in the response set, the decrease in Tau in the incompatible condition may have arisen in the special case where there are only two items that are in the response set. Studies have shown that subjects are able to adopt strategies when the

number of response set items is relatively small (e.g., Logan, Zbrodoff, & Williamson, 1984). Such strategies may be more likely to influence performance when processing is slow and thus, the effects of such strategies may be largely in the tail of the RT distribution (see Logan, 1988 for similar arguments). By increasing the number of items in the response set, such strategies become increasingly difficult and the changes in Tau are eliminated. I now turn to the next experiment that attempts to modulate the interference effects by manipulating the processing strength of the targets and flankers.

Experiment 2

In Experiment 2, I test the hypothesis that the interference effects observed in Tau in the Stroop task are related to the asymmetry in SR strength between the relevant and irrelevant dimensions. It is possible that pattern of interference in the Stroop task is influenced by the fact that the distracting word is more strongly related to the required verbal response than is the color. To look at the contribution of SR asymmetry to the pattern of interference, Experiment 2 uses a variant of the flanker task. The words LEFT and RIGHT are used as words that are more strongly related to the response (left or right button press) than the words LARGE and SMALL. The latter words are related to the response only via the instructions that subjects receive at the beginning of the experimental session. When there is a mismatch in stimulus-response strength between the targets and flankers, the interference effects should be larger relative to when the targets and flankers are matched in strength. The central question is whether this increased interference effect is reflected only in the Mu component of the ex-Gaussian or whether interference will now be evidenced in the Tau component also. The distinction between spatial and nonspatial selection that I drew in Chapter 4 predicts that the interference effects observed in this task should be reflected only in the Mu parameter. This is because the spatial relations of the targets and distractors remains consistent with the original flanker task, namely interference effects only in Mu and no effects in Tau.

As discussed in Chapter 4, older adults should show deficits on those tasks that tap the nonspatial level of selection (e.g., Stroop task) and it is this level of selection that results in interference effects in the Tau component of the distribution. In contrast, older

adults should be less impaired in the spatial selection processes that result in the interference effects exhibited in the Mu parameter. Because this task requires the use of spatial selection, there should be no age differences in this task, aside from older adults being overall slower than the younger adults.

Methods

Participants

Twenty young adults were recruited from the undergraduate student population at Washington University and received course credit for participation. Young adults were between the ages of 18 and 21 years ($M = 19.5$, $SD = 0.9$) and had an average of 14.1 ($SD = .97$) years of education. Twenty older adults were recruited from the Aging and Development Subject Pool. The older adults were between the ages of 60 and 77 years ($M = 71.1$, $SD = 4.6$) and had an average of 14.9 years ($SD = 2.6$) of education.

Apparatus

The apparatus was the same as for Experiment 1.

Stimuli and Design

The target words appeared in the center of the screen with flanking words appearing above and below the target word with an offset of 12 pixels or approximately .5 degrees of visual angle. The words were written in Courier font with 8 by 8 pixel letters. The words were LEFT, RIGHT, LARGE, SMALL and BLANK. All words were displayed in upper case in white on a black background. The words LEFT and RIGHT were always assigned to the left and right response keys respectively. The words LARGE and SMALL were assigned equally often to the left and right response keys

across participants. The word BLANK was never assigned to any response and thus served as the flanker in the neutral condition.

As in the previous experiment, there were the traditional flanker conditions of Congruent, Incongruent Compatible, Incongruent Incompatible, and Neutral. In the present experiment, the direction words (LEFT and RIGHT) were strongly related to the response, while the other two words (LARGE and SMALL) were more weakly related to the response. The addition of the strength manipulation resulted in a partially nested design in which the strength of the flankers and targets could be totally crossed only in the Incongruent Incompatible condition (see Table 1). There were a total of 192 trials each in the congruent, incongruent-compatible, incongruent-incompatible, and neutral conditions. The incongruent-incompatible condition was further divided into 4 cells formed by crossing the target strength (strong or weak) and flanker strength (strong or weak). There were a total of 48 trials in each of these nested cells.

Procedure

For each trial, the following sequence of events occurred: a) three plus signs ("+++"") appeared in the center of the screen for 500 ms, b) the screen was blank for 200 ms, c) the center word appeared in the position of the plus signs and the flanking words appeared above and below the center word, and remained on the screen until the subject responded or until 2500 ms has elapsed d) once the participant made the response, the screen was cleared, e) there was a 1000 ms intertrial interval. In the event of an error, there was a 700 Hz tone for 500 ms and the message "**** Error ****" was displayed in the center of the screen for 1000 ms.

At the beginning of the experiment, participants were given 32 practice trials. Each condition was represented in the practice block in the same proportion as in the actual experiment. The sequence of events on the practice trials was exactly the same as for the experimental trials.

Participants were given breaks at the end of each block of 100 trials. Feedback in the form of speed and accuracy information was given after every block of trials. The entire experimental session lasted approximately 45 minutes.

Results

The response times were screened using the same criteria as in Experiment 1. A total of 1.79% of the responses were eliminated from the analyses. An analysis of the proportion of data trimmed as a function of condition did not suggest any differential trimming of data across condition ($F < 1.0$).

Mean RT Analyses

Because of the nested design of the present study, I first present analyses of the standard flanker conditions. As shown in Figure 17, the mean RT results follow very closely those observed in Experiment 1. The data were analyzed in a 2 (Age) by 4 (Flanker Condition) mixed factor ANOVA. The older adults were overall slower than the younger adults, $F(1, 38) = 28.79$, $MSE = 26520$, $p < .001$; and there were reliable differences between conditions, $F(3, 114) = 54.38$, $MSE = 150$, $p < .001$, but the Age by Condition interaction did not approach significance ($F < 1$). Relative to the neutral condition, separate comparisons showed interference in the incongruent-incompatible condition, $F(1, 38) = 23.36$, $MSE = 116$, $p < .001$, and facilitation in both the congruent-

compatible condition, $F(1, 38) = 81.36$, $MSE = 115$, $p < .001$, and incongruent-compatible condition, $F(1, 38) = 14.67$, $MSE = 187$, $p < .001$. In each case, the effect was very similar in younger and older adults ($F_s < 1$).

The primary goal of this experiment was to investigate interference in the flanker task by manipulating the strength with which the words were associated with the response. The next analyses break down the incongruent incompatible condition into the four cells formed by crossing the strength of the target with the strength of the flankers. The mean RT results as a function of target and flanker strength are reported in Figure 18. A 2 (Age) by 2 (Target Strength) by 3 (Flanker Strength, including neutral flankers) ANOVA revealed main effects of Age, $F(1, 38) = 28.30$, $MSE = 40438$, $p < .001$, Target Strength, $F(1, 38) = 7.13$, $MSE = 1779$, $p < .05$, and Flanker Strength, $F(2, 76) = 5.66$, $MSE = 505$, $p < .005$. Overall, strong targets were responded to faster than weak targets, and strong flankers were associated with slower responses than weak flankers. Finally, the analysis revealed a Target by Flanker strength interaction, $F(2, 76) = 13.05$, $MSE = 252$, $p < .001$. As shown in Figure 18, there was interference for weak targets displayed with strong flankers. There was also a reliable three way interaction, $F(2, 76) = 3.38$, $MSE = 251$, $p < .05$. Subsequent comparisons showed that there was reliable interference for strong targets both with weak flankers, $F(1, 38) = 28.79$, $MSE = 313$, $p < .001$, and with strong flankers, $F(1, 38) = 6.83$, $MSE = 256$, $p < .001$ and there were no reliable group differences in interference, ($F_s < 1$). For weak targets, there was reliable interference with strong flankers, $F(1, 38) = 8.99$, $MSE = 502$, $p < .005$ but not with weak

flankers, $F < 1$). For the weak targets with strong flankers, the interference was larger for the older adults than for the younger adults, $F(1, 38) = 3.47$, $MSE = 502$, $p = .07$.

The interference for strong targets that are flanked by weak flankers was surprising. It may be the case that when any of the words appeared on the screen, some retrieval of the associated response was initiated. For the words LARGE or SMALL this retrieval process was more effortful and attention demanding. It is clear from these results that the manipulation of target and flanker strength influences the size of the interference effect. The question is the extent to which these changes in the interference effects might be reflected in the RT distribution.

Error Analyses

Turning first to an analysis of the error rates for the four flanker conditions, the analysis indicated that the younger adults made marginally more errors than the older adults, $F(1, 38) = 3.92$, $MSE = .0061$, $p = .10$. Overall, there was no effect of condition on error rates, ($F = 1.91$, $p > .10$) although there was an Age by Condition interaction, $F(3, 114) = 3.84$, $MSE = .0005$, $p < .05$. The error rates for the younger adults differed reliably across condition, $F(3, 57) = 4.95$, $MSE = .0005$, $p < .005$. For the younger adults, relative to the neutral condition, there were fewer errors in the congruent compatible condition, $F(1, 19) = 8.30$, $MSE = .0007$, $p < .01$, and the incongruent compatible condition, $F(1, 19) = 4.91$, $MSE = .0006$, $p < .05$ while the incongruent incompatible condition did not differ from the neutral condition ($F < 1$). For the older adults, there was no difference in error rates amongst conditions, ($F < 1$). Limiting our attention to just the incongruent-incompatible condition in order to examine the influence of target and

flanker strength, there were more errors made by the younger adults than the older adults, $F(1, 38) = 6.04$, $MSE = .0102$, $p < .05$; and more errors to the weak targets than to the strong targets, $F(1, 38) = 6.02$, $MSE = .0040$, $p < .05$. There was also a reliable Age by Target by Flanker interaction, $F(2, 76) = 4.43$, $MSE = .0009$, $p < .05$. The younger adults made more errors for weak targets than for strong targets, $F(1, 19) = 4.74$, $MSE = .0053$, $p < .05$. The older adults showed similar error rates across condition (all $p > .14$).

Ex-Gaussian Analyses

Each of the four cells in the incongruent-incompatible condition contained 48 observations. In order to obtain adequate fits to the ex-Gaussian distribution, one typically needs at least 100 observations. When the number of observations per cell per subject falls short of this, Vincentizing is used (Ratcliff, 1979). This procedure involves rank ordering individual response times and calculating quantiles for individual participants (e.g., fastest 10%, next fastest 10% etc.). These quantiles are then averaged across a number of individuals to create supersubjects. This method allows one to smooth the empirical density function while preserving the overall shape of the distribution. Using Vincent averaging, two subjects were collapsed into a single supersubject, bringing the number of observations just slightly under the amount typically needed. This resulted in 10 supersubjects each in the young and older adult groups. For each supersubject the four cells in the incongruent-incompatible condition were fit as were the two neutral conditions (one with a strong target and one with a weak target). Thus, a total of 120 distributions were fit. The fits were good with none of the

distributions resulting in chi-squares values that exceeded the critical value at the .01 level.

As shown in Figures 19 and 20, the influence that the strength of targets and flankers had on the mean RT are reflected primarily in the Mu parameter. Indeed, the results of a 2 (Age) by 2 (Target Strength) by 3 (Flanker strength, including neutral) mixed factor ANOVA revealed results in Mu very similar to those observed in the mean RT analyses. Specifically, there were main effects of Age, $F(1, 18) = 113.61$, $MSE = 4265$, $p < .001$, Target Strength, $F(1, 18) = 5.21$, $MSE = 428$, $p < .05$, and Flanker Strength, $F(2, 36) = 3.81$, $MSE = 479$, $p < .05$, and there was an interaction between Target and Flanker Strength, $F(2, 36) = 6.20$, $MSE = 721$, $p < .005$. For the strong targets, relative to the neutral condition there was interference from weak flankers, $F(1, 18) = 23.62$, $MSE = 327$, $p < .001$ while there was no effect for strong flankers ($F < 1$). Analyses of the Sigma parameter revealed a reliable main effect of Target Strength, $F(1, 18) = 5.38$, $MSE = 143$, $p < .05$, and a Target by Flanker Strength interaction, $F(2, 36) = 3.94$, $MSE = 354$, $p < .05$. Importantly, there were no reliable main effects or interactions in Tau ($p > .18$) and, if anything, the effects in Tau are moving in the opposite direction to those in Mu. The lack of an age main effect in Tau suggests that the age difference in mean RT is a reflection of a shift of the distribution rather than any change in skewing. Moreover, there were also no interactions involving Age in any of the three parameters.

Discussion

The results suggest that it is possible to influence the interference effects in the context of a flanker task by manipulating the SR association strength between the target

and the flanker. However, despite this, interference effects continued to be observed only in Mu. Thus, these results suggest that the probability of observing interference effects in Tau is not simply a function of the asymmetry in target and distractor strength. These results appear to support the notion that interference effects reflected in the Tau parameter require the spatial integration of the relevant and irrelevant dimensions of the stimulus.

Another aspect of these results is that overall age differences in this task were carried entirely by Mu and Sigma. This contrasts with the prediction of general slowing that older adults' RT distributions should be a magnification of those of younger adults. In order for this to be the case, age differences would have to be equally distributed amongst all three parameters of the ex-Gaussian. The results of Experiment 2 show that this is not necessarily the case.

Experiment 3

If spatial information can be used to separate the relevant dimension from other competing dimensions of the display, the preceding experiments suggest that interference should be reflected largely in the Mu parameter of the ex-Gaussian. On the other hand, if spatial information cannot be used, then the selection process becomes more difficult and the resulting interference should also be reflected in the Tau parameter. This leads to the prediction that if the color and word dimensions of the Stroop task can be presented in separate locations in the display, then any resulting interference effects should occur only in the Mu and not in the Tau parameter. The goal of Experiment 3 was to test this prediction by utilizing a spatial version of the Stroop task. Moreover, because the modification of the Stroop task should eliminate the selection process that appears to be particularly deficient in older adults, the prediction is that the sizable age differences in the Stroop task observed by Spieler et al.(1996) should be eliminated by this modification of the task.

Method

Participants

Twenty two young adults were recruited from the undergraduate student population at Washington University and participated for course credit. Young adults were 18 to 22 years of age ($M = 19.8$, $SD = 1.3$) and had 13 to 16 years of education ($M = 13.7$, $SD = 1.2$). The twenty older adults were recruited from the Aging and Development Subject Pool and these individuals were 64 to 81 years of age ($M = 73.0$, $SD = 4.3$) and had 13 to 18 years of education ($M = 15.3$, $SD = 3.0$).

Apparatus

The apparatus was the same as in Experiments 1 and 2 with the exception that a Gebrands 1431T voice operated relay (VOR) interfaced with the computer allowed the measurement of vocal response onsets to the nearest *ms*.

Stimuli and Design

Four colors and the corresponding color names were used in the experiment: RED, BLUE, GREEN, YELLOW. In addition, there were four neutral words (DOG, BEAR, MOUSE, TIGER) used as distractors in the neutral condition. The words were presented in Courier font and each letter subtended approximately .1 degree of visual angle. The color consisted of a rectangular patch of uniform color 30 pixels wide and seven pixels tall. The color patch always appeared at the fixation. The word appeared either 35 pixels above the fixation or 30 pixels below. The position of the color and the word remained constant for each subject and was counterbalanced across participants.

The colors and words occurred in the following combinations: the congruent condition consisted of 128 trials (4 color words and matching color names x 32 occurrences of each); the incongruent condition consisted of 121 trials (4 colors x 3 nonmatching color names x 11 occurrences of each); and the neutral condition consisted of 128 trials (4 colors x 4 neutral words x 8 occurrences of each). This resulted in 377 trials total in the experiment.

Procedure

Each trial consisted of the following sequences of events: a) a fixation consisting of three plus signs ("+++") appeared in the center of the screen 500 *ms*, b) the screen

went blank for 200 ms, c) the stimulus appeared and remained on the screen until the VOR was triggered by the participant's naming response, d) the experimenter pressed one of 5 keys coding the response (4 keys corresponding to 4 colors and one key corresponding to a VOR error), e) the screen cleared for a 1000 ms intertrial interval prior to the start of the next trial.

At the beginning of the experiment, 32 practice trials were presented to familiarize the participants with the task. The sequence of events was exactly the same as for the experimental trials. During the experiment, participants were given breaks at the end of each block of 50 trials. Feedback in the form of speed and accuracy information was given after every block of trials. The experiment lasted approximately 45 minutes.

Results

The response times were screened using the same criteria as in Experiments 1 and 2. A total of 1.38% of responses were eliminated from the analyses. An analysis of the proportion of data trimmed as a function of condition did not suggest any differential trimming of data across condition ($F < 1.0$).

Mean RT Analyses

As shown in Figure 21, the older adults were slower than the younger adults, $F(1, 40) = 10.01$, $MSE = 33771$, $p < .005$, and both groups showed interference and facilitation effects relative to the neutral condition, $F(2, 80) = 139$, $MSE = 672$, $p < .001$. The older adults also showed larger interference and facilitation effects than the younger adults, $F(2, 80) = 4.74$, $MSE = 672$, $p < .05$, although the effects were proportionately very

similar across group, ($F < 1$). The size of the Stroop effects in this study are quite consistent with previous studies that have looked at age differences in spatial versions of the Stroop task (e.g., Hartley, 1992).

Error Analyses

Also shown in Figure 21 are the error proportions for each condition. An analysis of error proportions revealed only main effect of condition, $F(2, 80) = 27.94, MSE = .0005, p < .001$. Relative to the neutral condition, there were more errors in the incongruent condition, $F(1, 40) = 31.06, MSE = .0004, p < .001$, and fewer errors in the congruent condition, $F(1, 40) = 7.86, MSE = .002, p < .01$. There was no difference between younger and older adults in error rates and there was no Age by Condition interaction ($F_s < 2, ps > .15$).

Ex-Gaussian Analyses

Turning to the ex-Gaussian analyses, the present experiment contained sufficient observations per cell per participant to allow the ex-Gaussian to be fit to each individual in each age group. A total of 106 distributions were fit using a chi-square test to evaluate goodness of fit. None of the chi-square values were significant at the .01 level indicating that the ex-Gaussian was fitting the empirical distributions quite well. As shown in Figure 22, the robust interference and facilitation effects observed in the analyses of mean RT were reflected entirely in the Mu parameter. Indeed, three separate 2 (Age) by 3 (Condition) mixed factor ANOVAs revealed reliable effects of condition in Mu, $F(2, 78) = 69.80, MSE = 1322, p < .001$, and in Sigma, $F(2, 78) = 29.99, MSE = 428, p < .001$, but not in Tau, $F(2, 78) < 1$. In Mu, there was reliable interference, $F(1, 39) = 24.01, MSE =$

1656, $p < .001$, and facilitation, $F(1, 39) = 75.66$, $MSE = 699$, $p < .001$. Relative to the neutral condition, Sigma estimates were larger in the incongruent condition, $F(1, 39) = 13.83$, $MSE = 661$, $p < .001$; and smaller in the congruent condition, $F(1, 39) = 14.93$, $MSE = 271$, $p < .001$. Interestingly, in terms of overall age differences, there were reliable main effects of Age in Mu, $F(1, 39) = 10.86$, $MSE = 19514$, $p < .005$, and Sigma, $F(1, 39) = 4.85$, $MSE = 1808$, $p < .05$, but not in Tau, $F(1, 39) = 1.90$, $MSE = 5501$, $p = .18$, replicating the pattern of age differences found in Experiment 2. Finally, in none of the parameters was there a Age by Condition interaction ($p > .20$). In general, the effects in Mu were slightly larger for the older adults than for the younger adults but this was not reliable.

Discussion

The results from this experiment were straightforward: Competition between the color and the word in the spatial Stroop task resulted in shifts of the RT distribution, with little change in the tail of the distribution. This is in marked contrast to the results of previous Stroop experiments that used integrated stimuli and found that interference influenced both Mu and Tau (Heathcote et al. 1991, Spieler et al., 1996). Another noteworthy result is that the age difference in overall speed was found only in Mu and Sigma and not in Tau. This is surprising given that a general slowing account would predict that older adults' RT distributions should be magnifications of those of younger adults. For this to be the case, there would have to be Age differences in all three of the parameters. Thus these results provide further evidence that general slowing models that

have been formulated at the level of mean RT do not appear to be consistent with analyses at the level of RT distributions.

The results for the spatial Stroop task also rule out the possibility that response modality might account for task differences in interference effects. Until this experiment, experiments that have shown only Mu effects have been those tasks requiring button press responses while experiments showing Tau effects have required verbal responses. The spatial Stroop task preserves a number of important characteristics of the standard Stroop task including the verbal response. The fact that interference in this task was observed only in Mu indicates that differences in response modality cannot account for task differences in interference effects.

Experiment 4

Experiment 4 examines the effect of interference in the Simon task. In Simon-type tasks, individuals are shown stimuli and told to respond to the identity of the stimulus and to ignore the spatial position of the stimulus. For example, one might see the word LEFT printed on the right side of a computer screen. When the response required by the identity of the stimulus and its position conflict, individuals are slower to respond compared to when the two are consistent. The general explanation for this effect is that the spatial representation of the display has some overlap with the spatial representation that is used to generate the response (e.g., Kornblum, Hasbroucq, & Osman, 1990). Research has suggested that the locus of the Simon effect is at the response selection stage (Hommel, 1995; see Lu & Proctor 1996, for review). Thus, this experiment affords the opportunity to examine interference at another locus in processing.

Method

Participants

Twenty seven young adults were recruited from the undergraduate student population at Washington University and participated for course credit. Young adults were 17 to 23 years of age ($M = 19.7$, $SD = 1.3$) and had 13 to 17 years of education ($M = 14.2$, $SD = 1.1$). Twenty older adults were recruited from the Aging and Development Subject Pool. The older adults were 61 to 78 years of age ($M = 70.4$, $SD = 4.8$), and had 13 to 20 years of education ($M = 14.9$, $SD = 2.6$).

Apparatus

The apparatus was the same as that used for Experiments 1 and 2.

Stimuli and Design

The words were presented in Courier font with 8 x 8 pixel letters and each word subtended approximately .3 degrees of visual angle. The words used in this experiment were LEFT and RIGHT. Words were displayed in upper case in white on a black background. The words LEFT and RIGHT were assigned to the left and right response keys respectively. These words appeared offset by 120 pixels from the center of the computer screen. The words were displayed such that the middle of the word was approximately 2.5 degrees of visual angle to the left or right of the initial fixation. Each word (LEFT and RIGHT) was paired with each position 75 times resulting in 150 observations each in the congruent and incongruent conditions.

Procedure

On each trial, the following sequence of events occurred: a) a single plus sign ('+') appeared in the center of the screen for 500 ms b) the screen was blank for 200 ms, c) the word appeared either to the left or to the right the fixation and the onset of the word was coincident with the offset of the fixation, d) the word remained on the screen until the subject responded or until 2500 ms has elapsed. In the event of an error, there was a 700 Hz tone for 500 ms and the computer displayed the message "**** Error ****" in the center of the screen for 1000 ms. There was a 1000 ms intertrial interval.

Thirty two practice trials were given at the beginning of the experimental session. These practice trials contained equal numbers of congruent and incongruent trials and the sequence of events on the practice trials was identical to that in the actual experiment.

During the experiment, participants were given breaks at the end of each block of 100 trials. Feedback in the form of speed and accuracy information was provided after every block of trials. The experimental session lasted approximately 30 minutes.

Results

The response times were screened using the same criteria as in the preceding experiments. A total of 1.1% of the responses were eliminated for young adults and 2.0% of the responses for the older adults. While there were significantly more RTs trimmed from the older adults than the younger adults, $F(1, 45) = 14.58$, $MSE = .0002$, $p < .001$, there was no differential trimming that occurred across any of the cells in the design ($p > .19$).

Mean RT Analyses

As shown in Figure 23, the older adults were overall slower than the younger adults, $F(1, 45) = 123.17$, $MSE = 17024$, $p < .0001$. In addition there was a reliable compatibility effect, $F(1, 45) = 37.59$, $MSE = 760$, $p < .001$, and there was some tendency for the older adults to show a larger compatibility effect than the younger adults, $F(1, 45) = 13.67$, $MSE = 583$, $p < .05$. However, if one takes overall differences in processing speed into account by looking at the proportional effects (e.g., Burke, White, & Diaz, 1987; Spieler, Balota, & Faust, 1996), one finds that the compatibility effect size is .0339 in the younger adults and .0500 in the older adults. Thus there is a slight but nonsignificant increase in the compatibility effect for the older adults ($p > .15$).

Error Analyses

An examination of error proportions suggested that the overall age difference in speed and in the size of the compatibility effect was partly due to a speed accuracy tradeoff. Overall, the younger adults committed more errors than the older adults, $F(1, 45) = 26.86$, $MSE = .0022$, $p < .001$. There were also more errors committed in the incompatible condition than in the compatible condition, $F(1, 45) = 24.63$, $MSE = .0009$, $p < .001$. Younger adults also showed a larger compatibility effect than older adults in error rates, $F(1, 45) = 3.34$, $MSE = .0009$, $p = .07$, suggesting that a speed accuracy tradeoff may have contributed to the slight increase in the compatibility effect in the older adults compared to the younger adults.

Ex-Gaussian Analyses

Turning to the ex-Gaussian analyses, there were two questions that these analyses address. The first question is whether the effect of interference in the Simon task is similar to that observed in the Stroop task and results in interference in both the Mu and the Tau parameters or if response competition influences only the Gaussian component. The second question is what, if any, age differences are there in the parameters of the ex-Gaussian. To address this, two ex-Gaussian distributions were fit to each participant, one for the compatible and one for the incompatible conditions. Goodness of fit was evaluated using a chi-square which indicated that of the 54 distributions fit in the younger adults, three reached significant chi-square values at the .01 significance level. For the older adults, two of the 40 distributions were significant at the .01 level. Because all of these chi-square values were very close to the critical value, the parameter estimates for

these distributions were included in following analyses. Analyses that excluded these distributions were qualitatively identical.

The results of the ex-Gaussian analyses are shown in Figure 24. There were age main effects in all three parameters, Mu, $F(1, 45) = 109.34$, $MSE = 5974$, $p < .001$, Sigma, $F(1, 45) = 21.66$, $MSE = 349$, $p < .001$; and Tau, $F(1, 45) = 42.13$, $MSE = 995$, $p < .001$. The effect of compatibility was also reliable both in Mu, $F(1, 45) = 88.97$, $MSE = 385$, $p < .001$; and in Tau, $F(1, 45) = 16.26$, $MSE = 339$, $p < .001$. However, the effects in Tau were in the opposite direction of effects in Mu. There was also a reliable Age by Compatibility interaction in Mu, $F(1, 45) = 18.88$, $MSE = 385$, $p < .001$; and a marginal Age by Compatibility interaction in Tau, $F(1, 45) = 3.71$, $MSE = 339$, $p = .06$. Both of these interactions reflected slightly larger effects in the older adults than in the younger adults. Thus, contrary to the suggestion that there might be a parallel between the Stroop effect and the Simon effect, it appears that the pattern of parameter estimates in the Simon task is more similar to that observed in the flanker and local/global tasks. Indeed, opposite effects in Mu and Tau is similar to that observed in the original flanker task.

Discussion

The results of Experiment 4 indicate that competition at the level of response selection primarily influences the Gaussian component of the RT distribution. Thus, spatial selection and response selection stages appear to have their primary influence on the Gaussian component of the distribution. These results argue quite strongly against the analogy that was drawn between Stroop and Simon effects (Lu & Proctor, 1995;

O'Leary & Barber, 1993) because the influence that these two effects have on the RT distribution are quite different.

In the Simon task, there was a reversal in the Mu and Tau effects just as seen in the original flanker experiment. There are a number of experiments that suggest that the longer it takes an individual to get to the response selection stage, the smaller the Simon effect (Hommel, 1995). The account for this is that there is transient activation of the response that occurs with the onset of the stimulus. This activation of the corresponding response that slows response selection for incompatible displays (and likely speeds selection for compatible displays). When more time elapses between the onset of the stimulus and the selection of the response, this transient activation has time to decay and this results in less competition. The smaller Tau estimates in the incompatible condition compared to the compatible may result because for the slow responses that fall in the tail of the RT distribution, the competing response has decayed more, resulting in less response competition. In the next section, I present analyses that support this interpretation. Of course, it remains for further studies to determine if this reversal is consistent across multiple versions of the Simon task.

Chapter VI: Supplementary Analyses

Before turning to a discussion of the theoretical implications of these findings, there are three issues that might constrain the interpretation of the present results and each may be addressed through supplementary analyses of the present experiments. Thus, it is an examination of each of these issues that I shall turn to next.

Effect Size

The first issue concerns the relationship between the overall effect size and the probability of observing effects in the Tau parameter. The Stroop task reported by Spieler et al. (1996), had large interference effects in Tau and the overall size of the interference effect was in the range of 100 ms. However, interference effects in the present experiments tend to be smaller, in the range of 20 to 40 ms. There is evidence that it is not simply the case that all manipulations that have large effects also result in effects in Tau. For example, when individuals are asked to decide if two words rhyme, “rhyme” decisions are, on average, approximately 100 ms faster than “no rhyme” decisions and this difference in mean RT is reflected entirely in Mu (Balota & Spieler, 1997). Nevertheless, it is possible that with larger effect sizes it may be easier to observe effects in Tau. To examine the relation between effect size and Tau, I computed interference effects in mean RT for each individual in the spatial Stroop task and performed a median split on the size of the interference effect for younger and older adults. This divided each group into those individuals that showed large and small interference effects. As shown in Figure 25, the overall interference effect for older adults showing large interference effects was in excess of 100 ms. This effect size in the range

of the Stroop effects reported by Spieler et al., where the interference effects were both in Mu and Tau. As can be seen in Figure 25, there is no evidence for effects in Tau even for those individuals that show large interference effects overall. This observation was supported by separate 2 (Age) by 2 (Effect Size) by 3 (Condition) mixed-factor ANOVAs for the Mu and Tau estimates. There was a reliable Size by Condition interaction, $F(2, 76) = 11.33$, $MSE = 992$, $p < .001$ in Mu but no such interaction in Tau, $F(2, 76) = 1.18$, $p > .30$. This suggests that the interference effects were entirely in the Mu parameter and this was independent of the size of the effect. These results appear to rule out overall effect size as a major determinant of effects in Tau.

Possible Trade-offs Between Parameters

A second concern is that across the results of the present experiments and the Stroop results of Spieler et al, there appears to be a negative relationship between Sigma and Tau. In experiments where there are effects in Tau there are typically small effects in Sigma and where there are no effects in Tau there are typically large effects in Sigma. Consistent with this, Spieler et al. reported that correlations between Sigma and Tau were generally negative. One concern is that the parameters of the ex-Gaussian might tradeoff one another. Such a tradeoff would clearly complicate the interpretation of the results. Of course, if the two parameters were somehow trading off one another, then the relationship between Sigma and Tau should be negative. In order to test this possibility, I correlated the estimates of Sigma and Tau across subjects for the Simon and spatial Stroop tasks. Interestingly, in both cases the correlations were small, *positive*, and nonsignificant (.07 to .31). This pattern also held when the data for both younger and

older adults were analyzed separately in each task. Thus, it does not appear that Sigma and Tau are trading off one another at least in these experiments.

Quantile Plots

The third concern deals with the adequacy of fitting theoretical functions for empirical data. Clearly, it is important to demonstrate that the theoretical functions are capturing all of the relevant aspects of the data. Moreover, it is unwise to rely exclusively on goodness-of-fit statistics to evaluate the ability of the theoretical function to capture the empirical data. A test of the ability of the ex-Gaussian function to capture the data is to plot the data in a model-independent fashion. If there are consistent changes in the RT distributions across tasks, then the differences that are suggested by the ex-Gaussian analysis should also be apparent when plotting the actual empirical data. To examine how distributions differ across conditions, the simplest approach is to divide individual conditions into multiple quantiles and plot each condition in each task as a function of quantile. Thus, one might plot the mean for the fastest 20% of the data, next fastest 20%, etc. for each condition. To the extent that the ex-Gaussian analyses are capturing consistent changes in the shapes of RT distributions, it is possible to predict the trend of between condition differences as a function of quantile. Because Tau is primarily a reflection of the later portion of the distribution, fast quantiles should show effects that are primarily a reflection of effects in Mu while slower quantiles should reflect the effects in both Mu and Tau. When there are differences between conditions in the same direction in Mu and Tau, differences between the two conditions should increase from the fastest to slowest quantiles. However, if effects in Mu and Tau are in the opposite

direction, then the difference between conditions should decrease from the fastest quantiles to the slowest quantiles.

Recall that in the Stroop task, the incongruent condition shows both larger Mu and larger Tau estimates relative to the neutral condition. If one divides each condition into equal 20% quantiles, the interference effects observed in Mu and Tau suggest that the differences between these two conditions should *increase* from the fastest to the slowest quantile. Furthermore, because there is an increase in Tau accompanied by a decrease in Mu in the congruent condition relative to the neutral condition, differences between these two conditions should *decrease* across quantiles. In Figure 26, I have plotted data for the younger adults from Stroop task reported in Spieler et al. Each condition was divided into five quantiles for each condition and each quantile was averaged across subjects. As can be seen, the difference between the incongruent and neutral conditions *increases* across quantile and the difference between the congruent and neutral conditions *decrease* (in fact there is a crossover) across quantile, consistent with the predictions derived from the ex-Gaussian analyses. I next plotted data from a task that showed only Mu effects. As shown in Figure 27, the data from the spatial Stroop task in Experiment 3 exhibit a pattern different from the standard Stroop shown in Figure 26. While there is an increase in the interference effect across quantile, this increase is considerably smaller than that shown in Figure 26. A similar quantile plot of the results from the Simon task in Experiment 4 is shown in Figure 28. Recall that in this task, the Mu and Tau effects were in the opposite direction which suggests that the difference between conditions should decrease across quantile. Consistent with this, the quantile

plot shows that the difference between congruent and incongruent conditions decreases across quantiles, again consistent with the observation that Mu and Tau are moving in opposite directions. These plots indicate that the ex-Gaussian analysis is, in fact, capturing consistent changes in the shapes of RT distributions.

If quantile plots allow one to capture these differences in RT distributions while not requiring one to assume a particular theoretical function for the RT distribution, then why not use the quantile analysis? One important reason for preferring the ex-Gaussian approach is that the parameters provide an intuitively accessible way for understanding how manipulations influence the shapes of RT distributions. For example, the ex-Gaussian analysis allows one to parsimoniously communicate the fact that interference in the spatial Stroop task shifts the distribution in a way that may not be immediately apparent from the quantile plots. Moreover, from these experiments and others (e.g., Balota & Spieler, 1997), it appears that the ex-Gaussian parameters tap theoretically meaningful components of the empirical RT distributions. Nevertheless, the quantile plots do provide an important check on the ability of the ex-Gaussian analyses to capture meaningful changes in the data and these plots may be useful in circumstances where the amount of data is not sufficient to obtain stable parameter estimates for the ex-Gaussian distribution.

Chapter VII: General Discussion

The goal of this research was to examine the influence of selective attention processes on the shapes of underlying RT distributions. There has been considerable research in the past three decades exploring how competition in selective attention influences mean response time (RT). However, a number of studies have shown that effects observed in mean RT are reflective of a variety of effects on characteristics of the underlying RT distribution from which the mean RT is computed (Hockley, 1984; Heathcote et al, Ratcliff, 1978; Ratcliff & Spieler, 1997; Spieler, et al, 1996). By fitting the ex-Gaussian distribution to empirical RT distributions, it is possible to describe the RT distribution using three parameters, Mu, corresponding to the leading edge of the distribution, Sigma, corresponding to symmetric variability of the distribution, and Tau, corresponding to the slow tail of the distribution. Studies using this method to analyze data from the Stroop task have found that the interference in this task was in both Mu and Tau (Heathcote, et al.; Mewhort et al, Spieler, et al.; see Figure 8). Moreover, Spieler et al showed that age differences in the Stroop task were entirely in the Tau parameter. Mewhort et al, also reported the results from a study using local/global figures (Navon, 1977) and found that interference in this task resulted in interference only in Mu. In Chapter 3, I reviewed the results of two experiments with both younger and older adults. The first experiment replicated and extended the results of Mewhort et al. using the local/global task by showing interference only in Mu and by showing that there were no age differences in the interference component of this task. The second experiment

reviewed in Chapter 3 used Eriksen and Eriksen's flanker task and these results also showed interference entirely in Mu and again, no age differences were found.

One of the characteristics shared by the local/global and flanker tasks is that spatial information is used to select the relevant information while the use of spatial information in the typical Stroop task is not possible. Based on this, I suggested that under conditions where spatial selection can be used, interference effects should only occur in Mu. However, the flanker experiment from which data were reported in Chapter 3 was idiosyncratic in the sense that it used a smaller stimulus set than other studies in the literature. Experiment 1 provided a replication of these results using an expanded stimulus set more comparable to other studies in the literature. The results of Experiment 1 replicated the finding that interference in the flanker task is only in Mu.

The distinction between spatial and nonspatial selection is only one of a number of differences between the flanker and local/global tasks and Stroop task. Another difference is that, in the Stroop task, the irrelevant word is more strongly related than the color to the required verbal response. Thus, there is an asymmetry in the strength of the stimulus-response association in the Stroop task that is not present in the flanker and local/global tasks. In these tasks, both the relevant and irrelevant letters are arbitrarily mapped to a button press and hence, are more closely balanced in stimulus-response strength. Experiment 2 used targets and distractors that differed in the strength of association with the response in the flanker task. The results of this experiment showed that this difference does not influence the effect that interference has on the shape of the

RT distribution. Even under conditions in which the strength of the mapping changes, the interference effect was still only in Mu.

Experiment 3 used a spatial variant of the Stroop task where a color patch and a word are presented in different locations in the display. This experiment preserved all of the characteristics of the standard Stroop task but simply spatially separated the color and word information. Thus, now spatial information could be used to select the relevant color patch. Consistent with the spatial selection hypothesis, interference in this task was only in the Mu parameter.

Experiment 4 employed a Simon-type task to examine competition at the response selection stage. In this task, individuals responded to the identity of the stimulus by making a left or a right button press. When the spatial position of the stimulus and the required button press mismatch (e.g., stimulus requires a left button press but appears on the right side of the computer screen), individuals are slower to respond compared to when stimulus position and response match (see Lu & Proctor 1995, for review). In the context of the present research, I derived two predictions about how interference in this task might influence the RT distribution. The first prediction was motivated by the parallel between the Stroop and the Simon tasks. In the Simon task, the spatial information is actually the competing attribute of the selected stimulus. Moreover, several researchers have drawn a parallel between Stroop effects and Simon effects (Lu & Proctor, 1995; Barber et al). Given this parallel, one might suggest that interference effects in the Simon task should be in both Mu and Tau. However, a large amount of previous research has indicated that interference in the Simon task occurs primarily at the

response selection stage (Umiltà, 1995; Hommel, 1993, 1995). In light of Hohle's (1965) original suggestion that effects in Tau are reflective of more central processes and Mu is reflective of processes that are more at the input and output ends of processing, the prediction was that interference should be largely in the Gaussian component of the distribution. The results showed that the compatibility effect in the Simon task is in the Mu parameter indicating that competition in either spatial *or* response selection acts to simply shift the distribution.

In the next section, I discuss two general computation approaches that provide some insight into the types of processes that might result in simple shifts in an RT distribution (change in Mu) versus both a shift and an increase in the skewing of an RT distribution (changes in both Mu and Tau). The two computational models that I focus on here are the diffusion model of Ratcliff (1978) and an extension of the cascade model of McClelland (1979).

Diffusion Model

In the diffusion model information accumulates for a particular response stochastically over time (Ratcliff, 1978; Ratcliff & VanZandt, 1996). The rate at which information accumulates is the drift rate and is determined by the strength of evidence favoring one response over the other. Moreover, this drift rate is variable from trial to trial. The model can generate predictions about the shapes of response time distributions and how the distributions change across conditions in an experiment. For example, if two experimental conditions differ in rate at which information accumulates to a response, then the diffusion model predicts that the RT distribution for the slower condition will be

both shifted up and more skewed than the faster condition (see Figure 14). This relationship between mean and the skew of the simulated distribution in the diffusion model is very difficult to alter (see Figure 14). As I have shown, experimental manipulations may act to shift the distribution without a concomitant change in the skew of the distribution. Within the diffusion model, a shift in the RT distribution with no change in skewing can be accomplished by decreasing the drift rate and *decreasing* variability of the drift rate. However, lower drift rates indicate less or weaker evidence favoring a particular response and the a priori prediction would be that in situations of greater uncertainty, variability would increase rather than decrease. An alternative to modifying the drift rate is to assume that the point in time at which information actually begins to accumulate toward a response is later in one condition compared to another. In the parameters of the diffusion model, one parameter represents both the time for encoding of the stimulus and the generation of the response and this parameter is a simple additive constant. Thus, one can shift the distribution by increasing this encoding and response parameter.

A fairly serious limitation of the diffusion model is that it is primarily intended to capture performance in two choice RT experiments. In situations where multiple response alternatives are possible, processing in a diffusion framework gets considerably more complicated because information drifts towards multiple boundaries in N dimensional space, where N is the number of responses. This emphasis on two choice RT tasks means that the model is best suited to situations such as the flanker task where there are only two response alternatives. However, I have already shown that the effects in the RT

distribution in the flanker task, namely a change in Mu with no change in Tau, are not easily accommodated in the diffusion model.

Cascade Model

The second general computational model is the cascade model of McClelland (1979). In this model, multiple processing stages intervene between the onset of a stimulus and the generation of the response. Each processing stage is active throughout processing and the output of each stage is continuously valued and always available to the next stage in the sequence. Thus, information propagates through the system from input to output in a cascadic fashion. Associated with each stage is a rate of information processing. It is assumed that the processing of some stages can be accomplished relatively quickly and will have a fairly fast rate of processing while other processes will have a generally slower information processing rate. McClelland (1979) showed that the behavior of the set of stages in cascade can be described by a single function that is closely approximated by a shifted exponential function. The rate of activation accumulation at the response stage is largely determined by processes with comparatively slow information processing rates. Such rate-limiting processes are the functional bottlenecks in the system. On the other hand, comparatively fast processes determine the intercept of the activation function (e.g., the point at which activation rises above zero; for detailed mathematical treatment of the cascade model, see McClelland, 1979; Ashby, 1982)..

While the cascade model has been applied primarily to interpreting speed-accuracy tradeoff functions (Wicklegren, 1977; Pachella & Pew, 1968; Reed, 1973), the

model can also make predictions for response time distributions. The activation functions used in describing the behavior of the system are exponential and a set of exponential processing stages results in a general gamma distribution (Ashby 1982; Luce, 1986; Townsend & Ashby, 1983). However, the gamma distribution describes the asymptotic performance of the system with no variability among parameters. The assumption of no variability allows for tractable, closed form mathematical solutions. The problem is that mathematical tractability is not the only consideration in building models and the assumption of no variability in processing seems questionable. Thus, the approach that I have taken is to assume that there is some normal variability in the information processing rate at each stage. In order to test the applicability of the cascade model to RT distributions, I allowed random variability in the rate parameters for each stage in processing. Response time distributions were generated by setting rate parameters for two processes, one fast and one slow (the slow rate was one fourth the fast rate) and on each trial selecting a rate for each process that was normally distributed about the rate value set for that process. The variability of the rate parameters were linearly related to the rate such that slower processes were also more variable. The only other parameter was the response criterion and this was invariant across trials. Response times are the time at which the activation function crossed the response criterion. As shown in Figure 29, the simulation suggests that if a manipulation influences the fast process, the result is to shift the distribution while a manipulation that influences the slow process results in both a shift and an increase in skewing of the distribution.

These results suggest that, within the cascade model, processes that are relative bottlenecks in processing (e.g., rate-limiting processes) are those that are most likely to produce the changes in the skewing of the distribution. This is consistent with the idea advanced by Hohle, that the exponential component of the RT distribution reflects the operation of central, presumably resource limited (e.g., Norman & Bobrow, 1974), and attention demanding processes.

However, there are two problems associated with this model. First, without corollary assumptions, the model predicts that occasionally no response will be made (Ashby, 1982). This can be fixed by assuming that individuals also impose a deadline on processing such that if no answer is available by the deadline, the individual will guess. Second, in contrast to the diffusion model in which there are two response alternatives, the cascade model only generates “a response” and says nothing about identity of the actual response. This is an advantage in the sense that there is no limitation to two choice RT tasks as is the case for the diffusion model. However, the model is clearly less constrained and cannot provide any account for aspects of performance such as error rates as can the diffusion model.

There is a more general problem that while there are situations where the models are able to mimic the empirical data patterns, they do not offer much in the way of specific information about the underlying cognitive operations. Such information about what underlies these influences on components of RT distributions comes from an examination of other tasks that have shown similar effects. I shall now turn to a discussion of these studies.

Differential Influences on Components of Distributions

There are a number of other studies that have modeled RT distributions using the ex-Gaussian and these studies have identified factors that have selective influence on the Tau parameter. For example, in the lexical decision task individuals are required to make word/nonword judgments for letter strings. Typically, high frequency words are judged as words more quickly than low frequency words and we (Balota & Spieler, 1997) have shown that the difference in response time between high and low frequency words is primarily in Tau. Building on earlier work of Balota and Chumbley (1984) we suggested that two processes underlie performance in the lexical decision task. The initial process yields information about a letter string's familiarity. For example, familiarity may be the extent to which the string follows the rules for English orthography and phonology, or the overall fluency of perceptual processing (Jacoby, 1991; Jacoby, Woloshyn, & Kelley, 1989). This familiarity information is available early in processing and individuals can make a fast word or nonword response if the letter string yields familiarity values that are very high or very low. However, for intermediate levels of familiarity, there is a second checking stage that must be engaged. This checking stage is slower, more analytic, and attention demanding. When this checking stage is engaged, the response time for that trial is delayed, and hence, it falls out in the tail of the RT distribution. Frequency effects in the lexical decision task are larger in Tau than in Mu because low frequency words are more likely than high frequency words to require this second stage of processing, resulting in more responses falling in the tail of the distribution.

In the two process account, repeating a word should increase the familiarity of the word and hence reduce the probability that the checking stage needs to be engaged. By reducing the probability of checking, fewer responses should fall in the tail of the distribution. Thus, repetition should primarily act by pulling in the tail of the distribution. Consistent with this prediction, we found that the primary influence of word repetition was to decrease the Tau parameter estimates. In contrast, because repetition boosts familiarity for nonwords also, the concomitant increase in familiarity should increase the probability of engaging the second checking stage. Thus, the prediction is that for nonwords, repetition should actually result in more responses falling out in the tail of the distribution. The results supported this prediction by showing an *increase* in the Tau parameter for the repeated nonwords relative to the nonrepeated nonwords. Finally, if one turns to a different task that does not demand the checking process (e.g., word naming), one finds effects primarily in Mu.

A similar account might be applicable to the results of the Stroop task. The integrated color and word dimension requires a level of selection more difficult and attention demanding than the spatial selection required in the other tasks. As the task becomes attention demanding, the probability of error increases and to maintain the high level of accuracy required in these tasks, individuals need to monitor their performance and occasionally recheck the results of processing. When the two dimensions conflict, a second checking stage is much more likely to occur, to ensure that an intrusion error (producing the word instead of the color) does not occur compared to when the two dimensions are unrelated. This increased rate of checking results in more responses

falling out in the tail of the distribution and hence, larger Tau estimates in the incongruent condition relative to the neutral condition. A similar checking process might also occur for the increased Tau in the congruent relative to the neutral condition. In two out of the three conditions, a response that matches the word would be an intrusion error. During processing, if there is a match between their response and the word, they should recheck their response to ensure that it is not an intrusion error. Thus, in the congruent condition there may be an added tendency to engage this checking process. However, this checking process is unlikely to be engaged in the neutral condition because there is little similarity between the neutral word and the response making it less likely that the word might be produced as an intrusion error.

The preceding account suggests that the checking stage is not invoked in the tasks showing only Mu effects. If spatial information is one of the primitives of the perceptual system (e.g., van der Heijden, 1992), selection may be accomplished more quickly and be less vulnerable to error. If the system is less susceptible to error, then there should be little need to closely monitor the results of processing to screen out the incorrect responses.

There is an interesting prediction that it should be possible to reduce or eliminate Tau effects in the Stroop task if one could reduce the probability of checking. However, an individual that did not recheck the results of processing might instead simply produce the first available response. The cost of doing this would be an increase in intrusion errors. In a study of Stroop performance in individuals with Alzheimer's disease, we (Spieler, Balota, & Faust, 1996) have shown that mildly demented individuals have close

to a 20% intrusion error rate. This suggests that these individuals are not monitoring their performance but rather, they produce the first available response. Consistent with the checking account for Tau effects, these mildly demented individuals show Stroop interference effects *only* in Mu and no effects in Tau, consistent with the absence of the second checking stage of processing.

Thus, the notion that a checking process is the cause of the Tau effects in the lexical decision task and the Stroop task is consistent with the available evidence. It remains for further studies to more fully specify the conditions under which such rechecking processes are used. At first, there might appear to be some conflict between the rechecking account and the results of simulations for the cascade model. Recall in the cascade model, Tau effects occurred when a manipulation influences the rate of a slow, rate-limiting process. This effect was not probabilistic as suggested by the checking process account. However, these two results are not really in conflict. A probabilistic effect could be easily accommodated within the cascade model because the form of the activation function at the response stage says nothing about the number of stages occurring prior to the response stage. Moreover, there always exists a weighted mixture of two stages that exactly mimics characteristics of a single stage (e.g., VanZandt & Ratcliff, 1996). Thus, the two accounts are simply two different levels of description.

Age, General Slowing, and RT Distributions

One of the predominant controversies in cognitive aging concerns the appropriate level for theoretical accounts for age-related changes in cognitive processing. One pattern of data that has received a considerable amount of attention is produced by

plotting older adults' mean RTs for a set of tasks against younger adults' mean RTs for the same tasks (e.g., a Brinley plot). As shown in Figure 30, the typical finding is that a simple linear function accounts for 90-95% of the variance. However, there is some debate concerning the theoretical implications of this relationship. On the one hand, some would suggest a global change in the speed of information processing is sufficient to capture most, if not all, age-related changes in cognitive processing (or at least almost all such changes). The sheer strength of the relationship would seem to leave little room for more specific theoretical accounts for local age-related changes. However, some researchers have sounded notes of caution in interpreting Brinley plots (e.g., Fisher & Green, 1996; Perfect, 1995).

At present, there is ample evidence for considerable between task variability in the nature of the young-old performance relationship. For example, Faust, Balota, Ferraro and Spieler (1997) derived a "global" slowing function that was the average across a wide range of tasks. However, in subsequent comparisons of individual tasks with this global function, almost 30% of task slowing functions deviated reliably from the global function. Thus, the high rate of slowing functions that deviate from the global function indicates that more task- and process-specific theoretical accounts for age effects are needed.

The results of the distributional analyses offer further support for the notion that global slowing functions alone are not sufficient to capture the range of age-related changes in cognitive processing. If all that changes as a result of aging is a general speed factor, then the global slowing function that is derived from Brinley plots of mean RTs

should be reflective of a slowing function that occurs at the level of individual response times. In other words, it should be possible to take a slowing function derived from a Brinley plot, multiply individual RTs by this slowing function, and generate the RT distribution for the older adults. In the parameters of the ex-Gaussian distribution, this would be reflected by the finding that age differences were equivalent for all three parameters. However, Spieler et al. (1996; see also Balota, Spieler, & Faust, 1995) and the present experiments both demonstrate that age differences are not equivalent across the three parameters. For the Stroop task, Spieler et al. showed that the increase in interference in the older adults relative to the younger adults was due to a two-fold increase in interference in Tau but no change in interference in Mu. In the flanker task in Experiments 2 and the spatial Stroop task of Experiment 3, ex-Gaussian analyses revealed age main effects in Mu and Sigma but not in Tau. This suggests that overall age differences in processing speed were reflected primarily by a shift in the RT distribution.

The results of the ex-Gaussian analyses indicates that the relationship between the speeded performance of younger and older adults is not the one predicted by most formulations of general slowing (e.g., Myerson, et al, 1991). Faust et al argued for considerable task specificity because of the high rate with which tasks deviated from a global slowing function. The present results suggest that age may differentially influence components of RT distributions across tasks. Thus, even if two tasks have similar slowing functions, it is possible that these tasks may differentially influence the underlying RT distribution, opening the door to even more task specific slowing functions. In this light, these results question the generality of general slowing.

Future Directions

Taken together, the present results demonstrate the utility of analyses of RT distributions. In particular, I have argued that the effects in Tau in the Stroop task and in the lexical decisions task share a common cause, namely that both involve processes by which individuals recheck the results of processing to avoid errors. This suggests that as processing becomes more difficult, it should be possible to influence the size of effects in Tau. In situations where individuals are given instructions to emphasize speed rather than accuracy, then engaging in the rechecking process should be less likely and Tau effects should be small. On the other hand, when individuals are given instructions emphasizing accuracy, this should encourage checking processes and hence accentuate Tau effects. Researchers have long suggested that older adults may be less willing to make errors of commission (e.g., intrusion errors), and it is frequently the case that error rates for healthy older adults are lower than for younger adults (see Kausler, 1991 for discussion). This increased emphasis on accuracy likely accentuates age differences in processing speed and makes it more likely that older adults will engage in the second checking stage of processing. Consistent with this, studies have found that the age differences between older adults and younger adults are frequently larger in the tail of the distribution in tasks that appear to emphasize rechecking processes (e.g., lexical decision and Stroop tasks, Balota, Spieler, & Faust, 1994; Spieler et al.). This suggests that it might be possible to influence the nature of age differences in characteristics of RT distributions by giving younger and older adults instructions differentially emphasizing speed versus accuracy.

On a more general level, the method of fitting RT distributions emphasizes the point that there is considerable richness in the empirical data. Unfortunately, cognitive psychologists have typically taken a fairly restricted view of response time data and by limiting our analyses to measures of central tendency, we have generally passed over important aspects of performance. While the specific purpose of the present research was to use distributional analyses to provide some insight into selective attention, the more general goal was to show that there are consistent changes in the nature of RT distributions that are not captured when analyses are limited to measures of central tendency. As such, this research should be seen as further support for the use of analyses of RT distributions to test extant theories and provide insights into the cognitive processes underlying performance.

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Table 1. Example Conditions in Experiment 2

| Flanker Condition | Target/Flanker Strength | Example Stimuli (Target/Flanker)* |
|--------------------------|-------------------------|-----------------------------------|
| Compatible/Congruent | Strong/Strong | right/right |
| | Weak/Weak | small/small |
| Compatible/Incongruent | Strong/Weak | right/small |
| | Weak/Strong | small/right |
| Incompatible/Incongruent | Strong/Strong | right/left |
| | Weak/Weak | small/large |
| | Strong/Weak | right/large |
| | Weak/Strong | small/left |
| Neutral | Strong/Neutral | right/blank |
| | Weak/Neutral | small/blank |

*Stimuli are displayed with flankers above and below central target.

Footnotes

¹ Random walk and diffusion models both are models of information processing. In a random walk process, information accumulates in discrete units through discrete units of time while in a diffusion process information and time are continuously scaled. Thus, a random walk process reduces to a diffusion process by reducing the size of the time steps and information increments to zero.

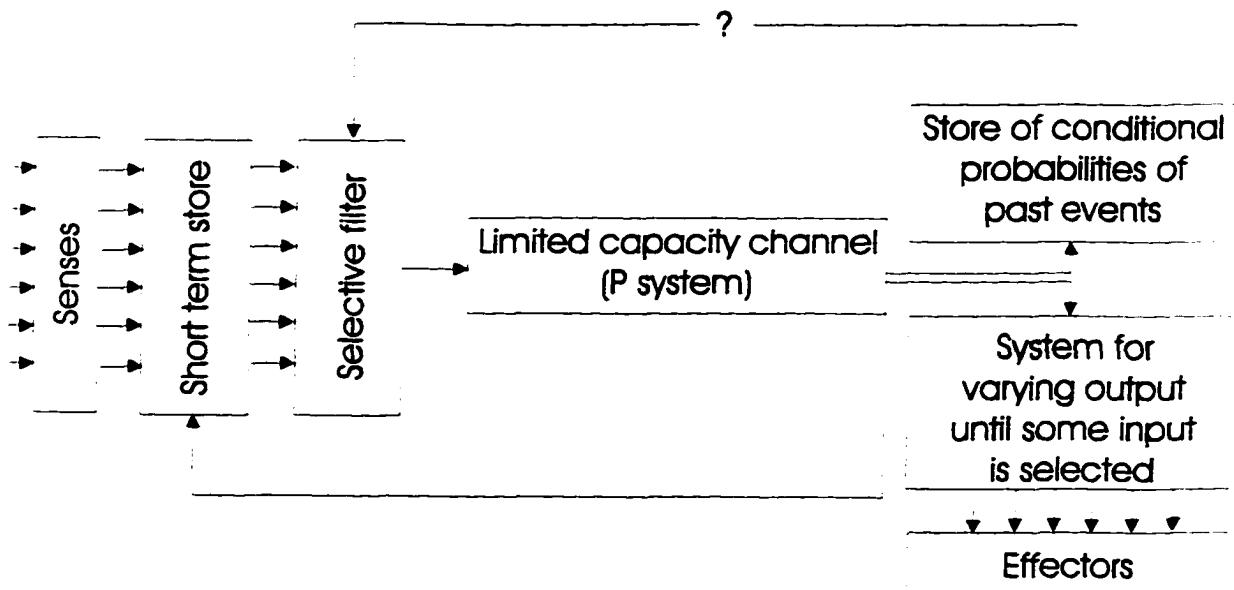
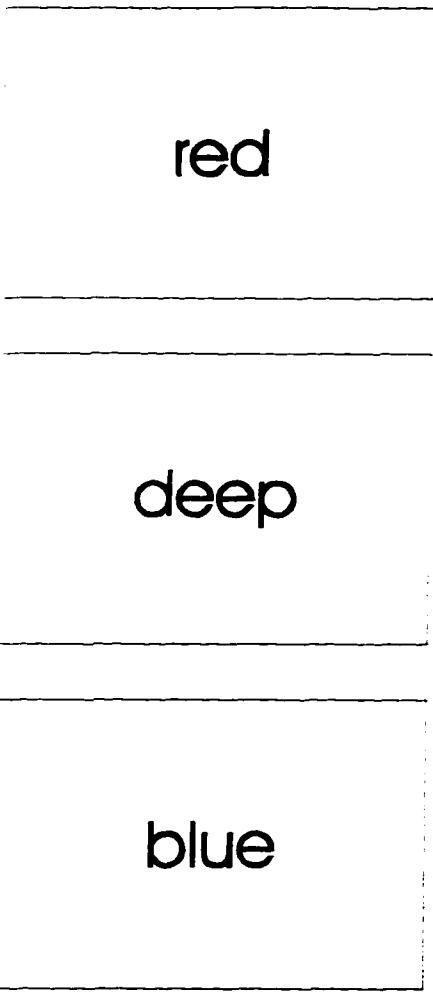


Figure 1. General processing model of Broadbent



red

deep

blue

Figure 2. Examples of congruent, neutral, and incongruent conditions of the Stroop task (if all words were printed in red).

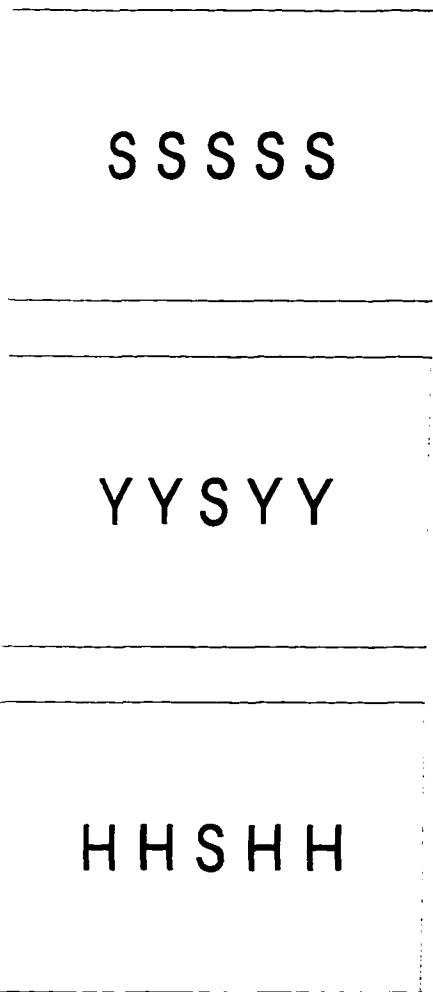


Figure 3. Examples of congruent, neutral and incongruent conditions of the flanker task.

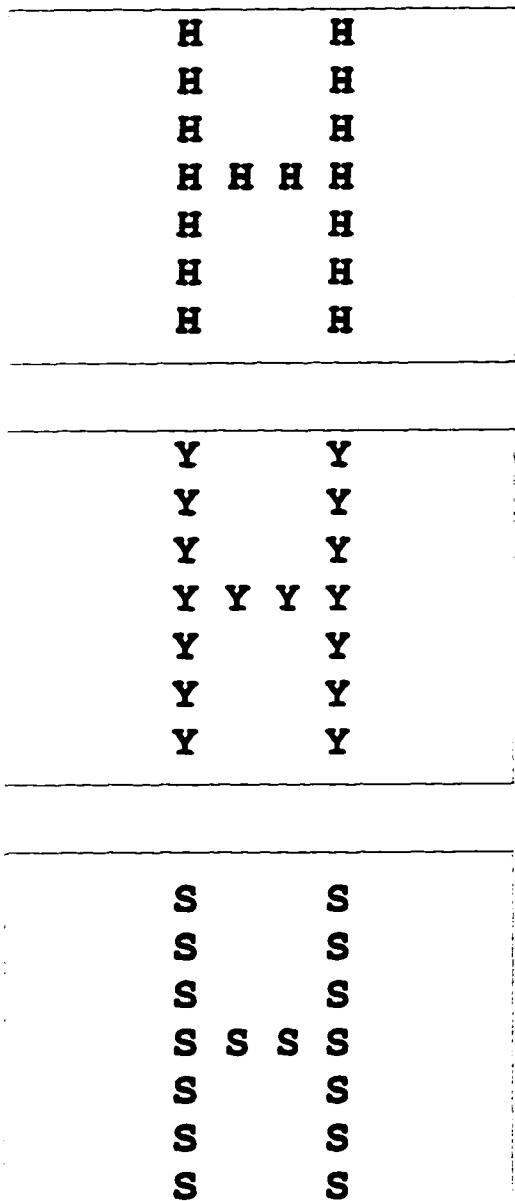


Figure 4. Examples of congruent, neutral, and incongruent conditions of the local/global task.

Sample Hazard Plot for RT data

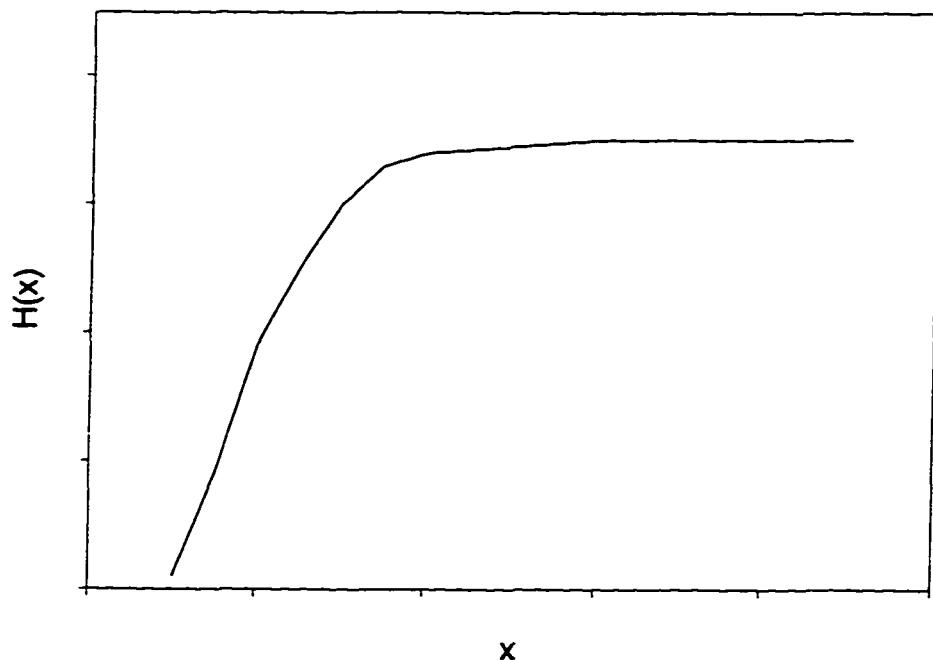


Figure 5. Example of a Hazard plot for empirical RT data.

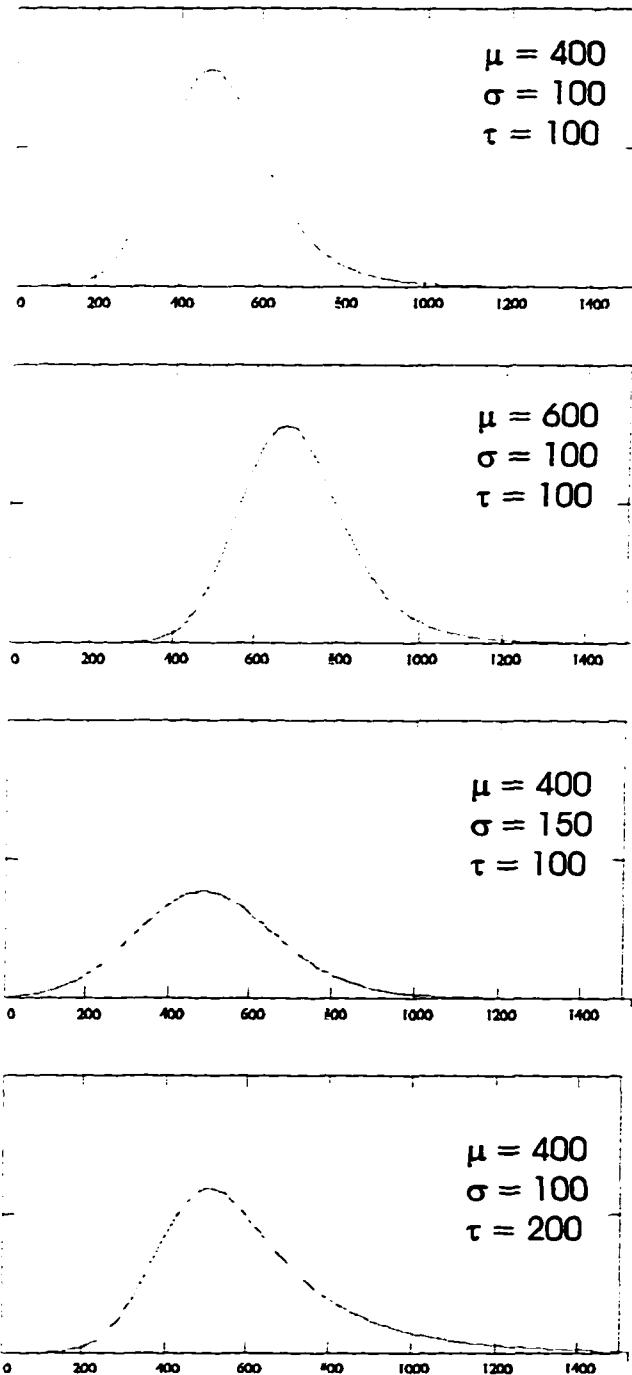


Figure 6. Examples of how changes in characteristics of RT distributions are reflected in changes in the parameters of the ex-Gaussian distribution.

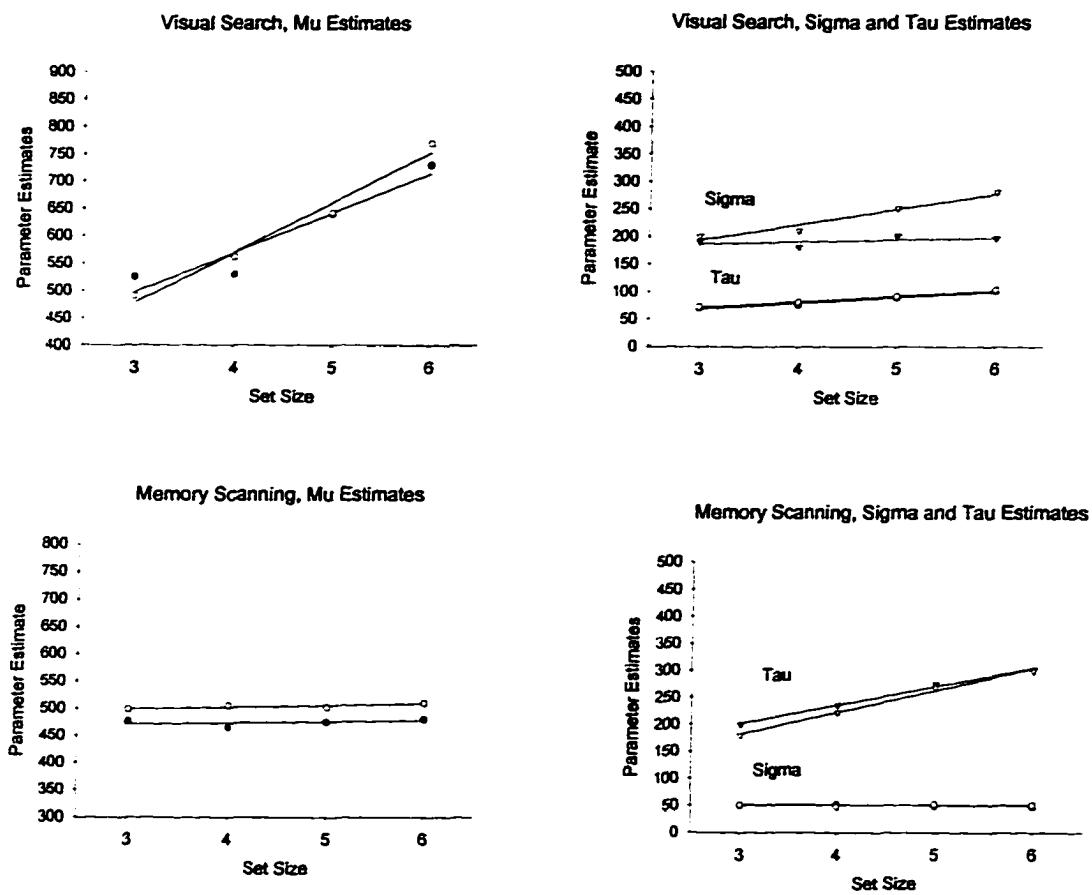


Figure 7. Results of visual search and memory scanning experiments. The open symbols are for the target absent condition and closed symbols are for the target present condition. The lines are the corresponding best fitting linear functions (adapted from Hockley, 1984).

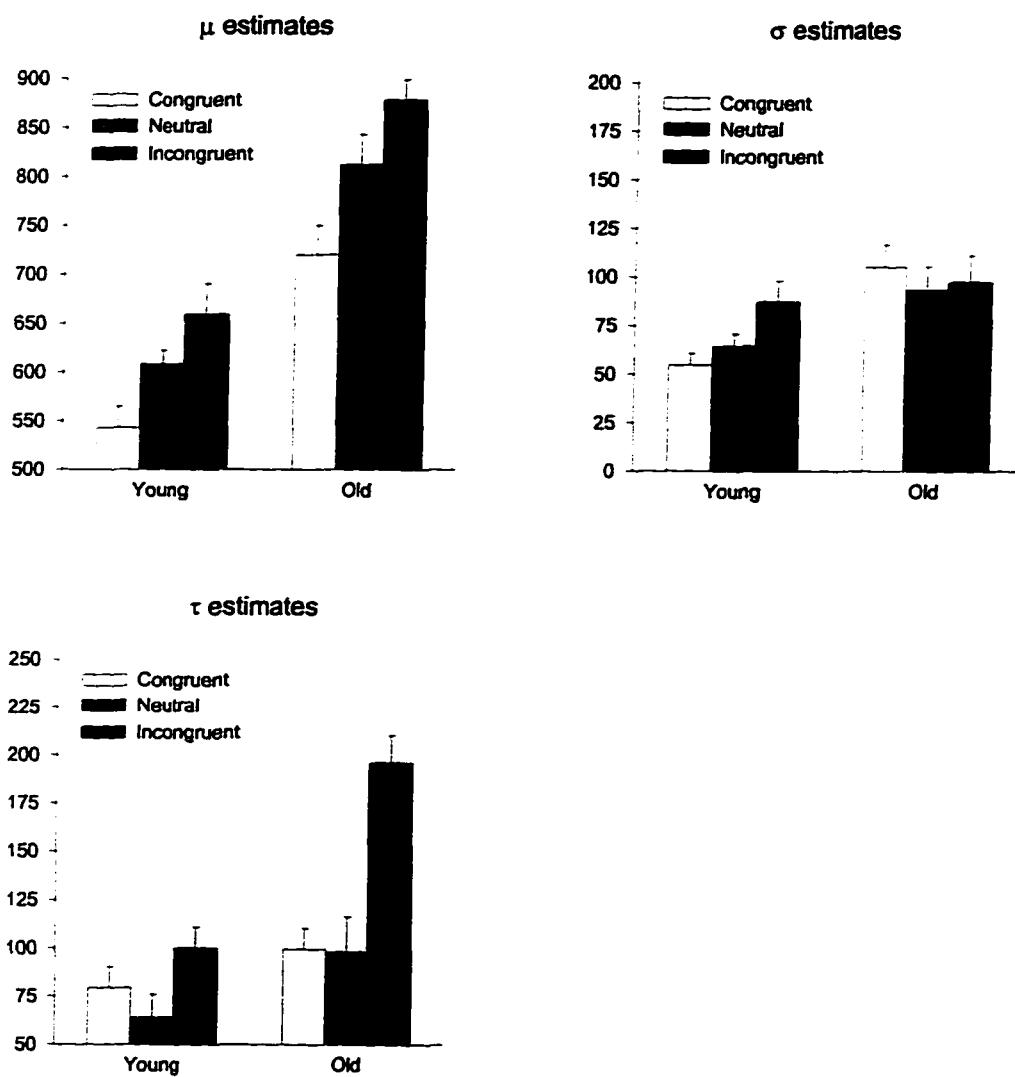


Figure 8. Ex-Gaussian parameter estimates parameter estimates for younger and older adults as a function of condition (adapted from Spieler, Balota, & Faust, 1996, Journal of Experimental Psychology: Human Perception and Performance). Error bars are one standard error.

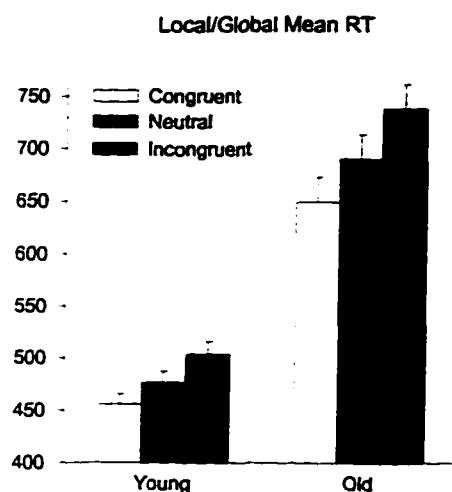


Figure 9. Mean RT results for younger and older adults in the local/global task as a function of condition. Data shown are for global responses only. Error bars are one standard error.

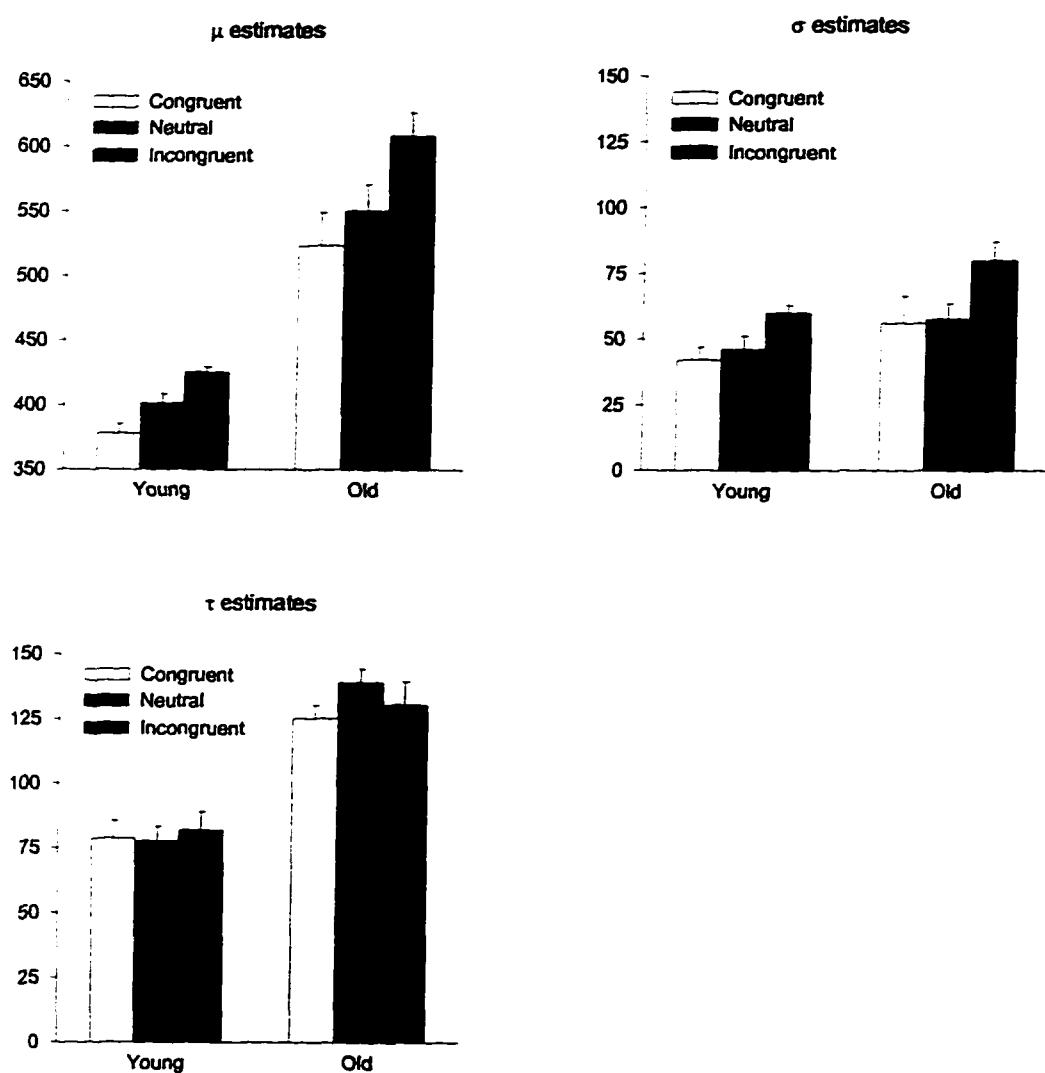


Figure 10. Ex-Gaussian parameter estimates for younger and older adults in the local/global task as a function of condition. Data shown are for the Global responses only. Error bars are one standard error.

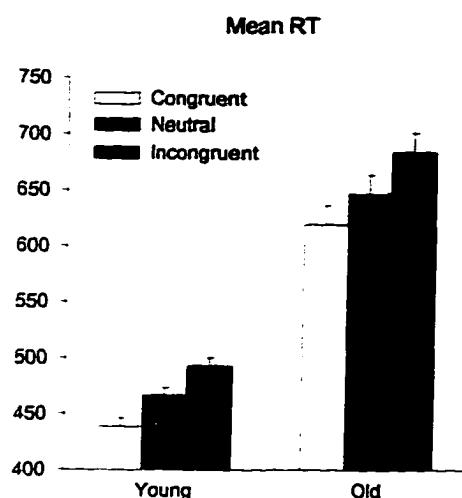


Figure 11. Mean RT results for younger and older adults in the flanker task as a function of condition. Error bars are one standard error.

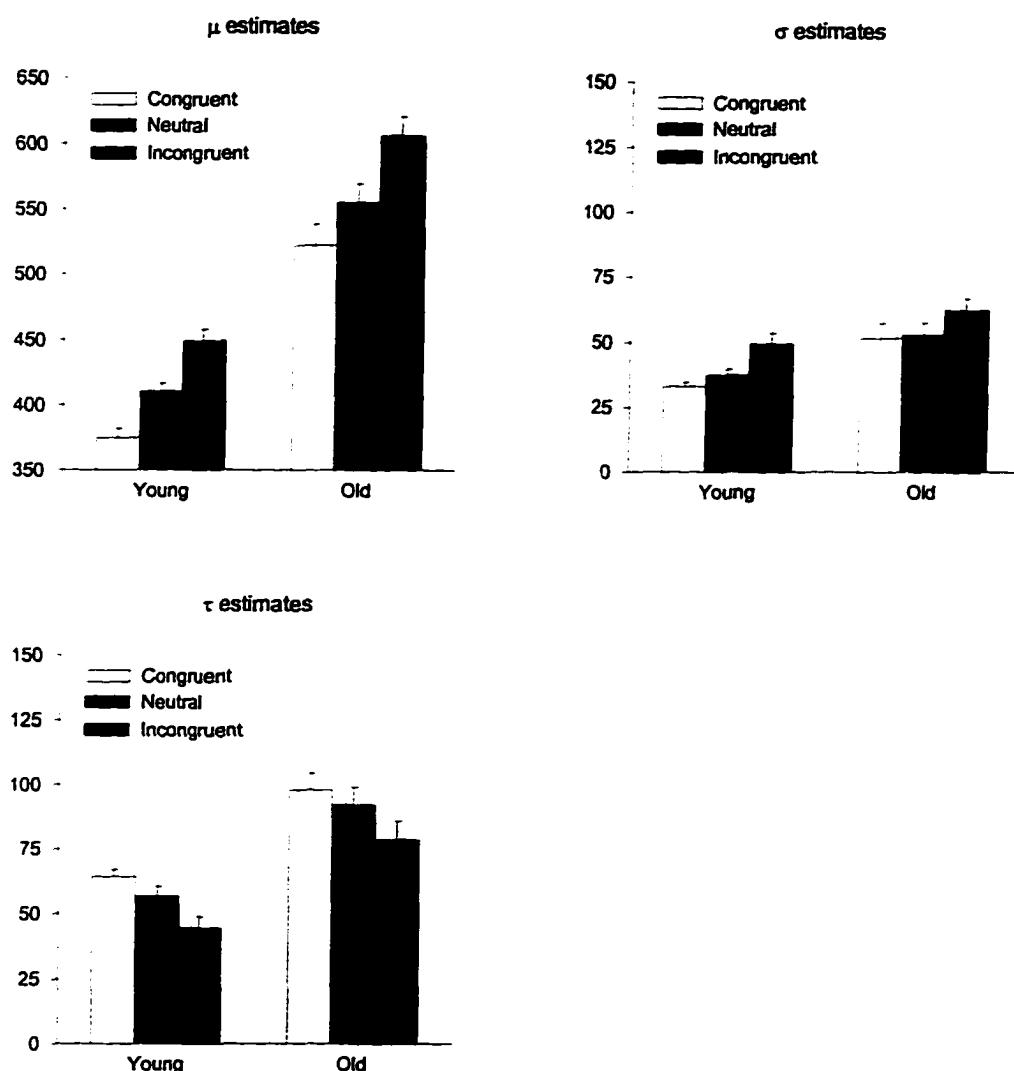


Figure 12. Ex-Gaussian parameter estimates for younger and older adults in the flanker task as a function of condition. Error bars are one standard error.

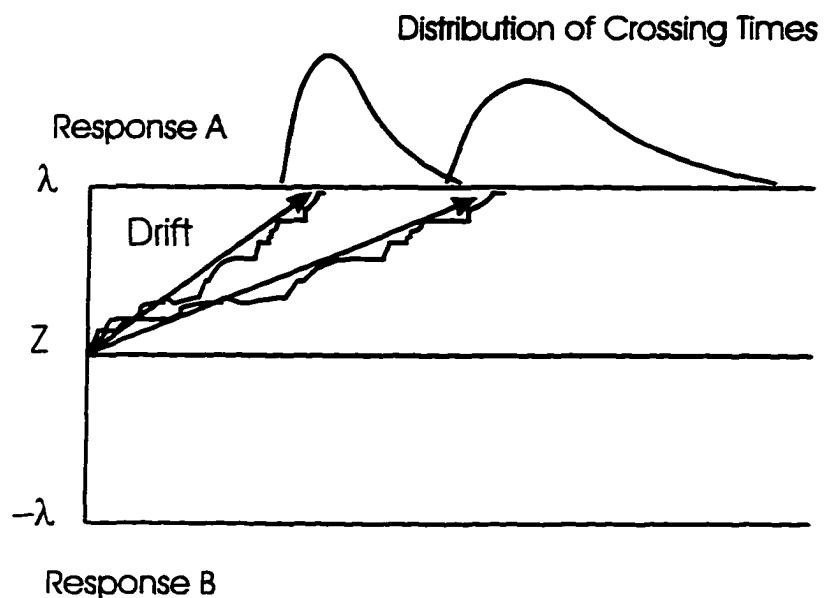


Figure 13. Diffusion model. Information accumulates stochastically over time. A response is made when one of the two boundaries is crossed. Variability from trial to trial results in a distribution of crossing times whose shape varies as a function of the drift rate.

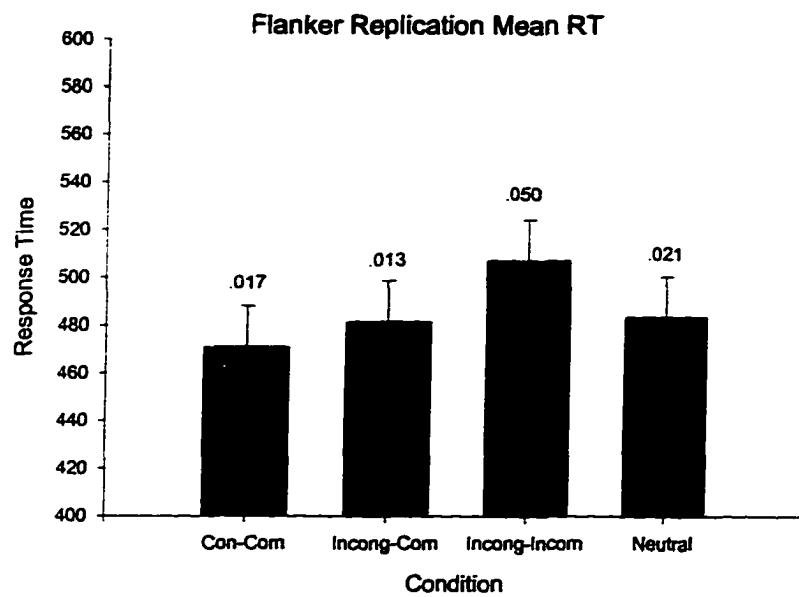


Figure 15. Mean RT results for Experiment 1 as a function of condition. Error rates are reported above each bar. Error bars are one standard error.

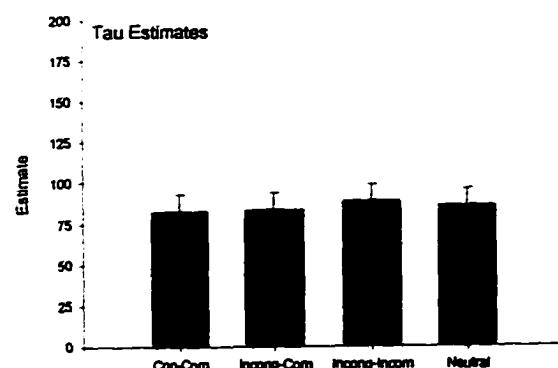
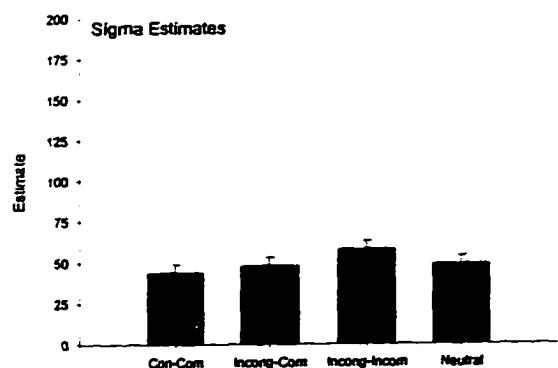
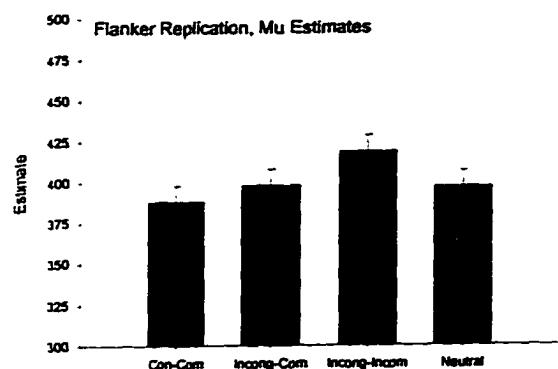


Figure 16. Experiment 1 results of ex-Gaussian analyses as a function of flanker Condition. Error bars are one standard error.

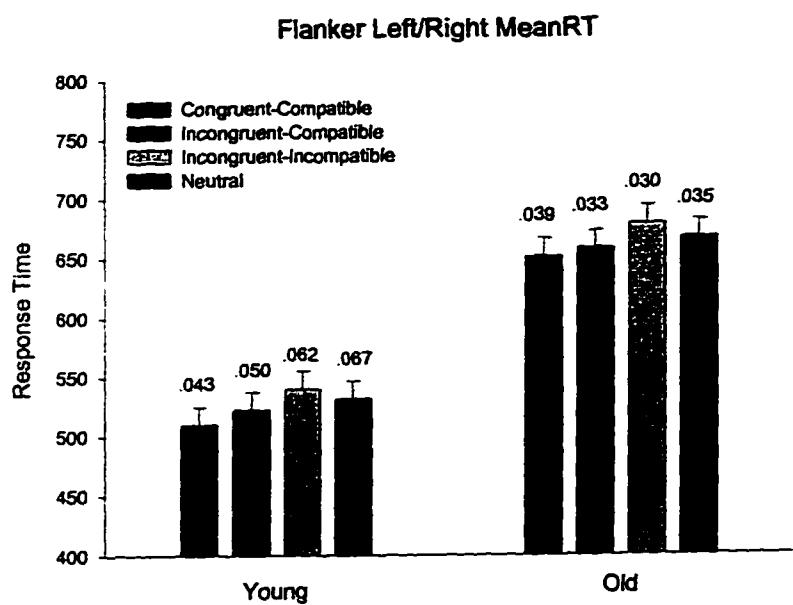


Figure 17. Experiment 2 MeanRT results as a function of flanker condition. Error rates are reported above each bar. Error bars are one standard error.

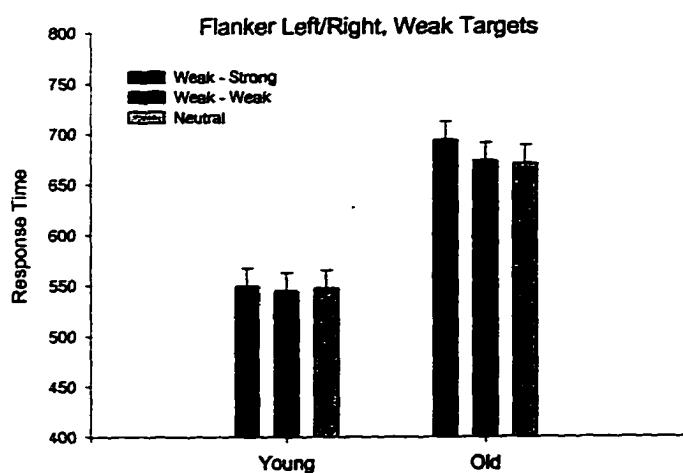
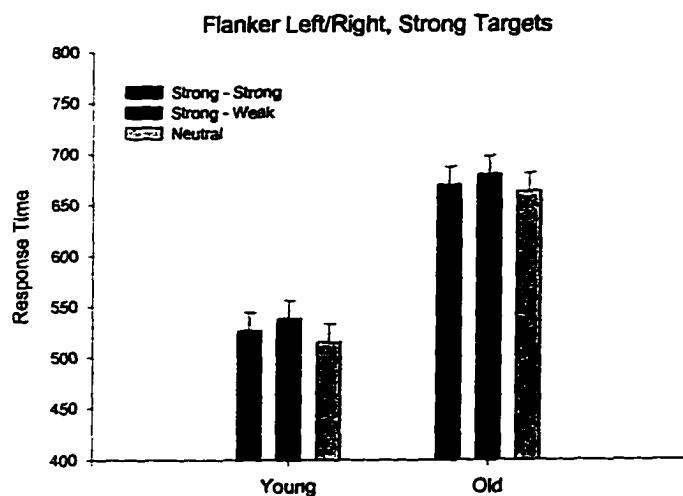


Figure 18. Mean RT results for strong and weak targets as a function of flanker strength for the incongruent-incompatible condition. Error bars are one standard error.

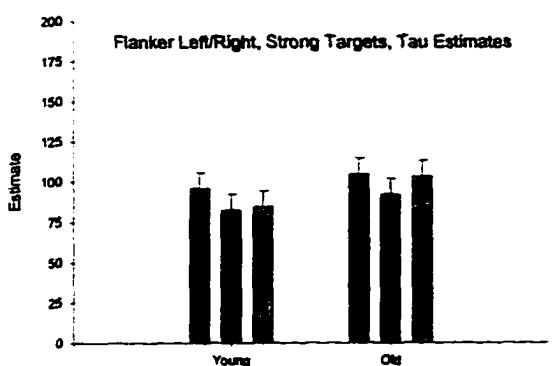
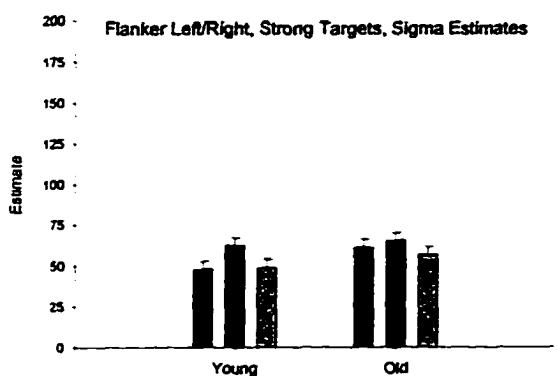
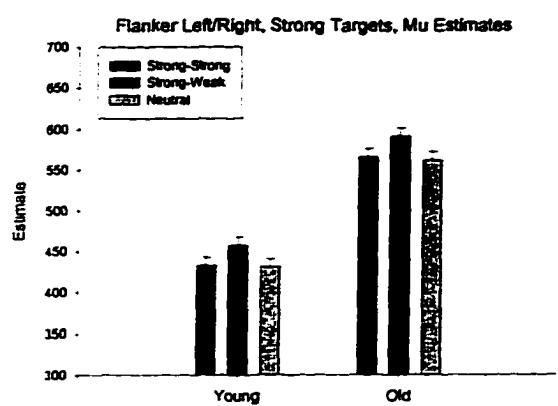


Figure 19. Ex-Gaussian parameter estimates for strong targets for younger and older adults as a function of flanker strength for the incongruent-incompatible condition. Error bars are one standard error.

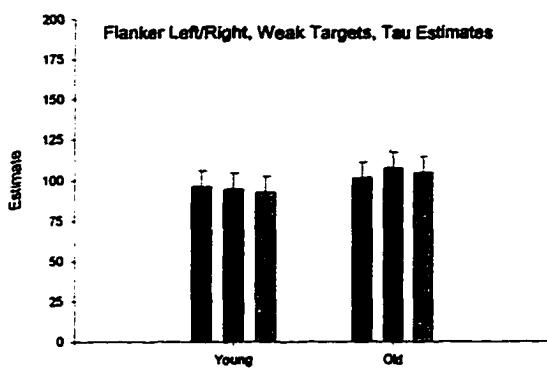
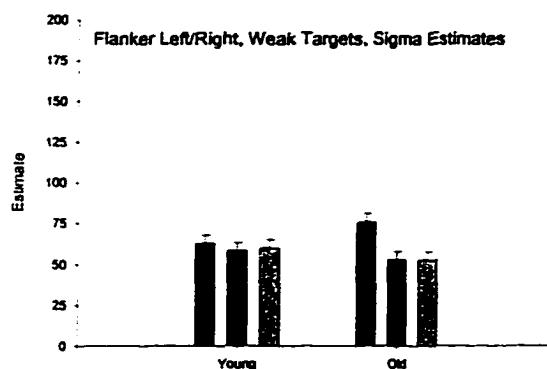
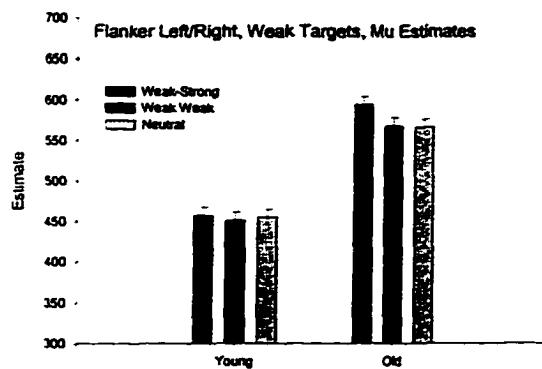


Figure 20. Ex-Gaussian parameter estimates for weak targets as a function of flanker strength for younger and older adults. Error bars are one standard error.

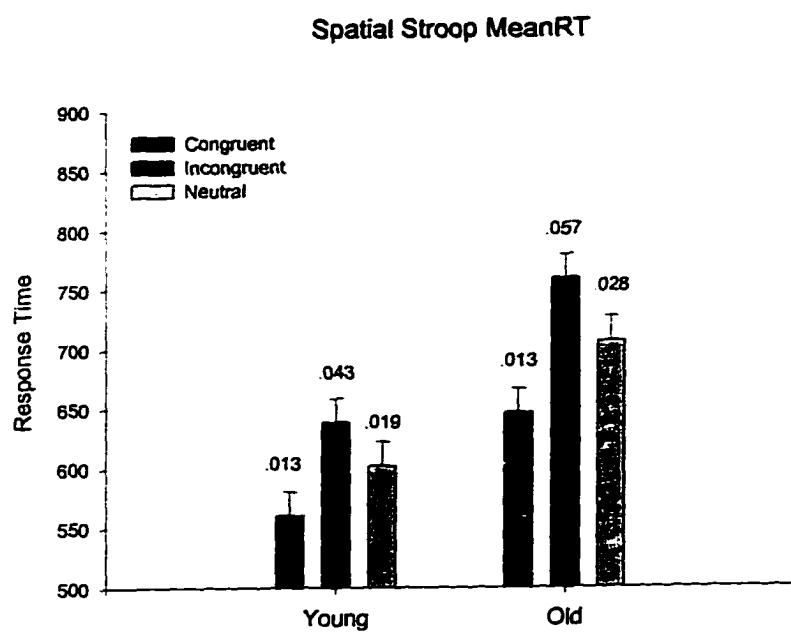


Figure 21. Mean RT results for the spatial Stroop task for younger and older adults as a function of Stroop condition. Error bars are one standard error.

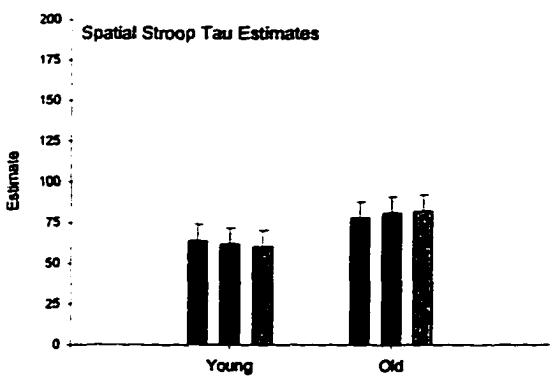
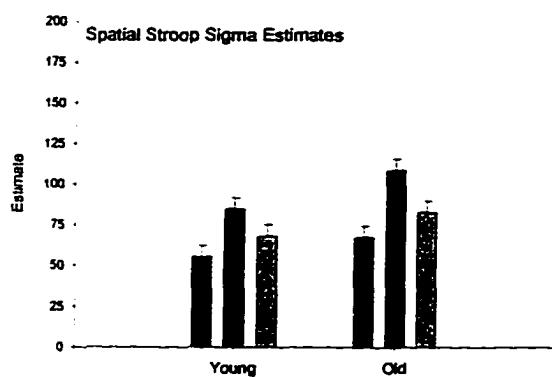
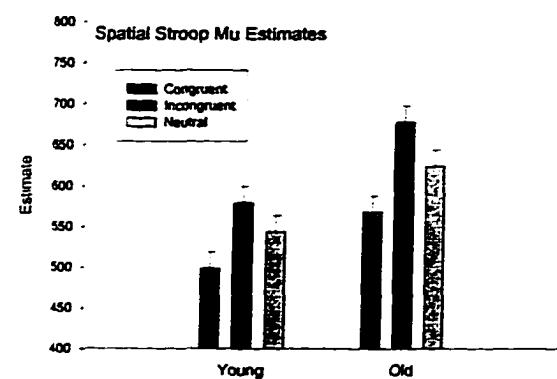


Figure 22. Ex-Gaussian results for the spatial Stroop task for younger and older adults as a function of Stroop condition. Error bars are one standard error.

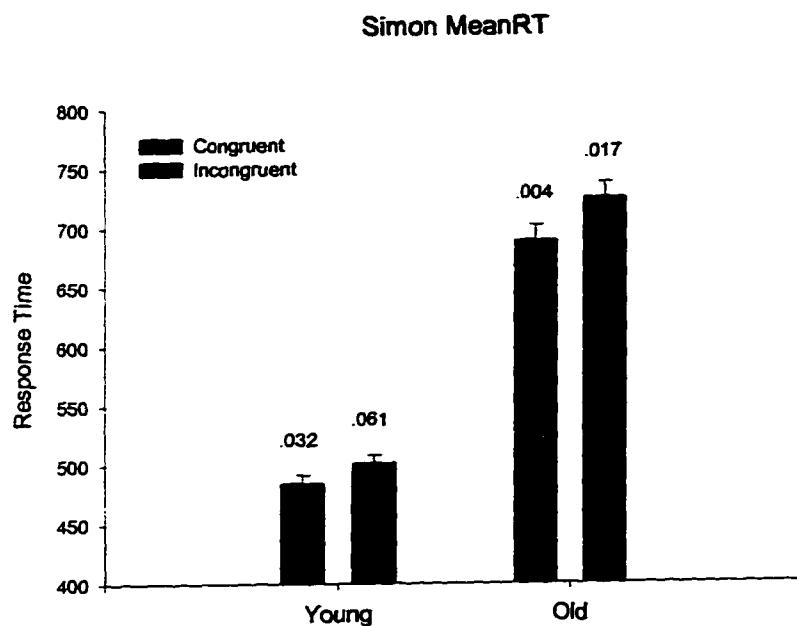


Figure 23. Mean RT results for the Simon task for younger and older adults as function of condition. Error bars are one standard error.

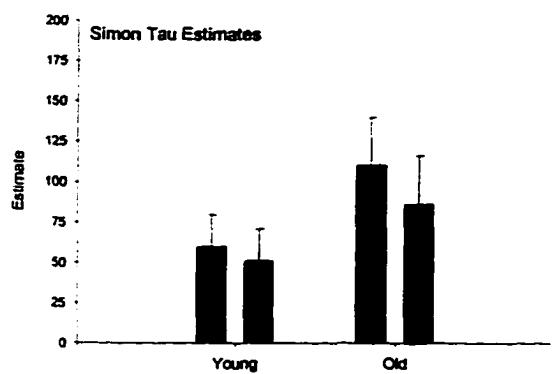
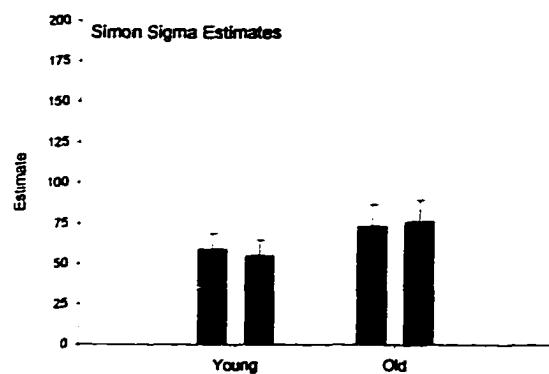
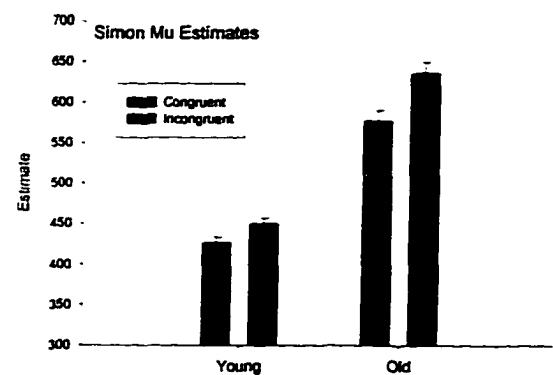


Figure 24. Ex-Gaussian parameter estimates for younger and older adults in the Simon task as a function of condition. Error bars are one standard error.

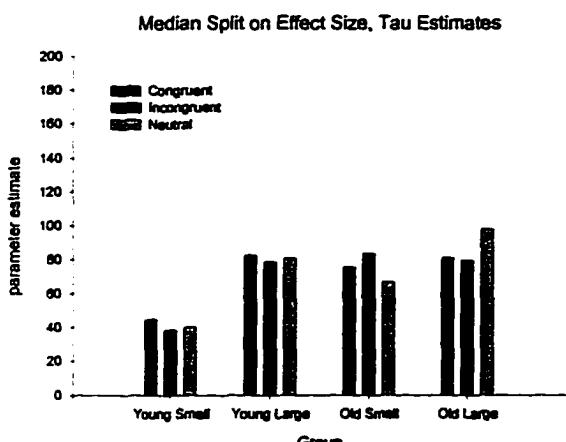
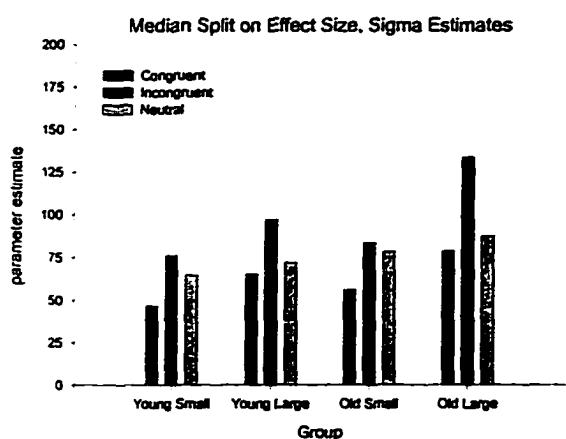
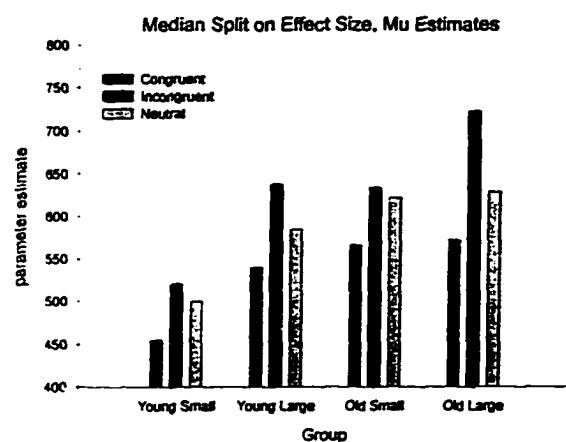


Figure 25. Ex-Gaussian parameter estimates from the spatial Stroop task as a function of effect size, age group, and Stroop condition

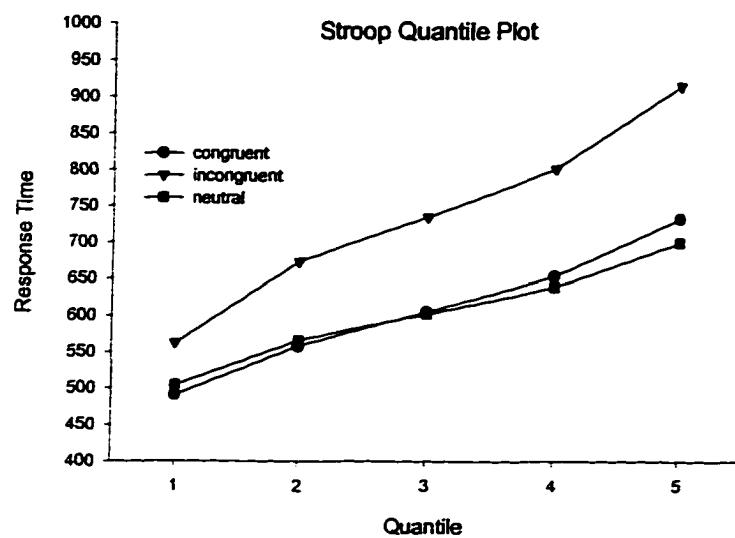


Figure 26. Mean RT for the Stroop task as a function of quantile and Stroop condition.

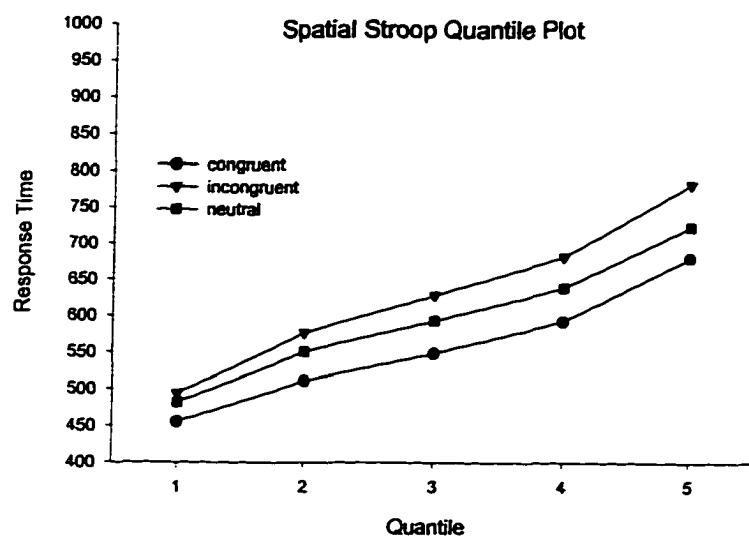


Figure 27. Mean RT for the spatial Stroop task as a function of quantile and Stroop condition.

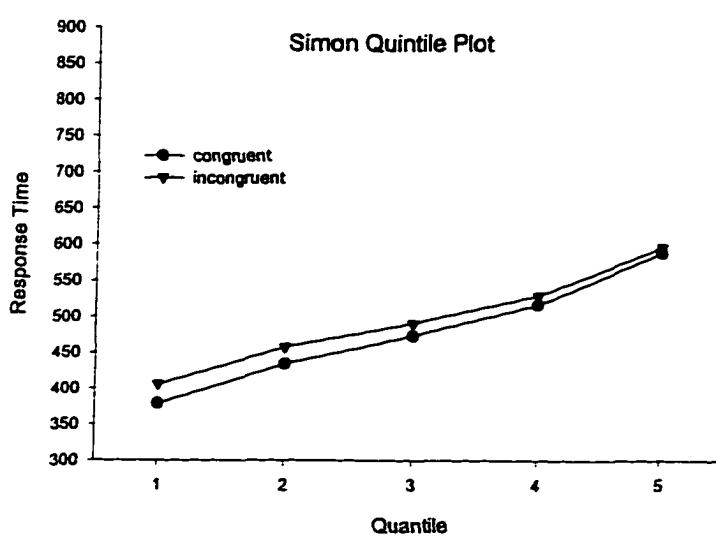
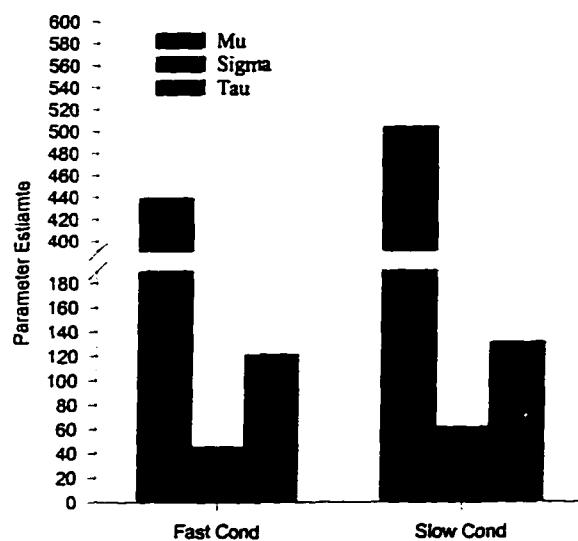


Figure 28. Mean RT for the Simon task as a function of quantile and condition.



Decrement in Processing Rate for Fast Process



Decrement in Processing Rate for Slow Process

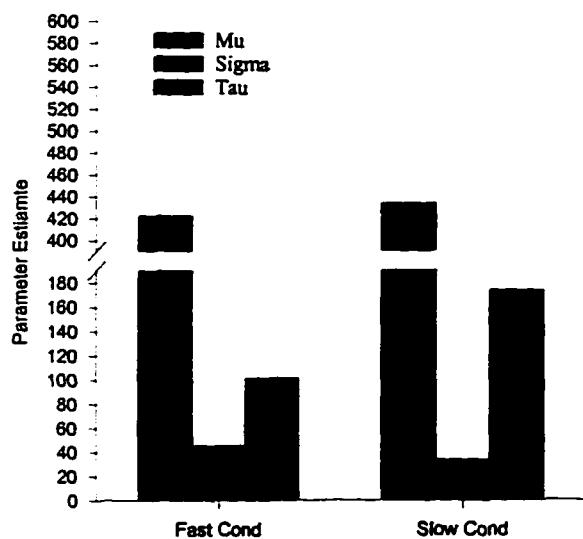


Figure 29. Predictions from the Cascade Model.

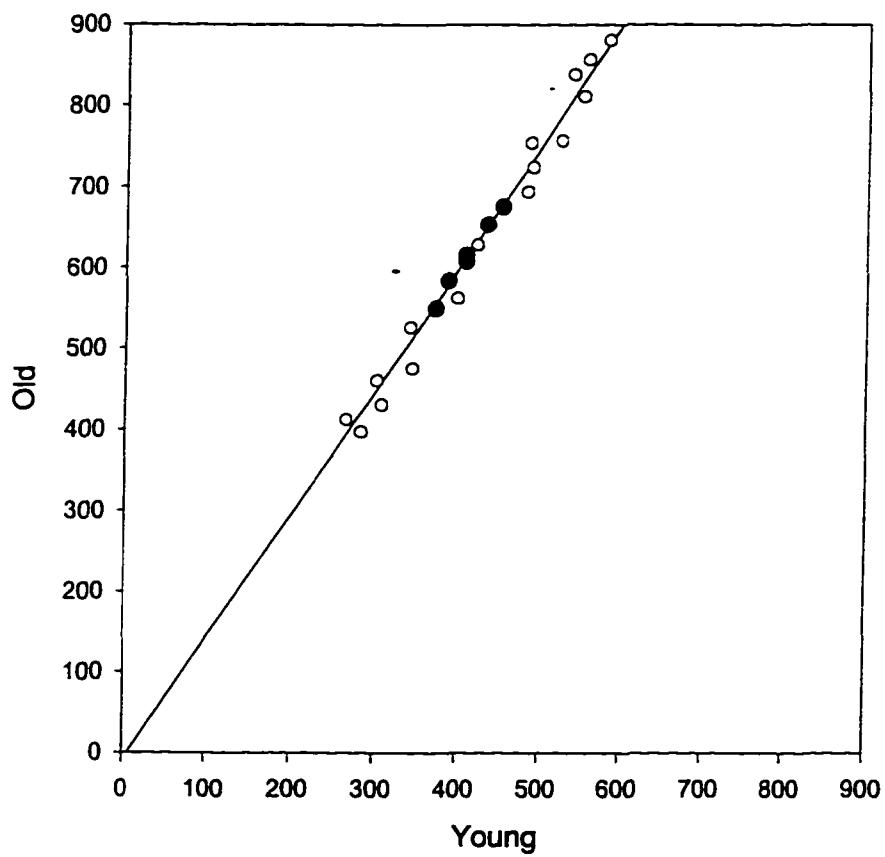


Figure 30. Example of a Brinley plot in which the mean RT for younger adults for a set of conditions are plotted against the corresponding mean RT for the older adults.