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# Notes and Comment

## Analysis of group differences in processing speed: Brinley plots, Q–Q plots, and other conspiracies

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*Researchers in a growing number of areas (including cognitive development, aging, and neuropsychology) use Brinley plots to compare the processing speed of different groups. Ratcliff, Spieler, and McKoon (2000) argued that a Brinley plot is a quantile–quantile (Q–Q) plot and that therefore Brinley plot regression slopes measure standard deviation ratios rather than relative speed of processing. We show that this argument is incorrect. Brinley plots, by definition, are not Q–Q plots; the former are based on unranked data and the latter are based on ranked data. Furthermore, the relationship between standard deviation ratios and slopes is a general property of regression lines and has no implications for the use of Brinley plot regression slopes as processing speed measures. We also show that the relative speed interpretation of Brinley plot slopes is strongly supported by converging evidence from a meta-analysis of visual search, mental rotation, and memory scanning in young and older adults. As to Ratcliff et al.'s hypothesis that age differences in response time are attributable to greater cautiousness on the part of the elderly, rather than true processing speed differences, this hypothesis has been extensively tested in previous studies and found wanting.*

> "Speed is God. And time is the devil."
> —David Hancock, computer executive, quoted in the *New York Times* (Markoff, 1996, p. D1)

As the preceding quote suggests, speed is critical to the performance of information processing systems, and this is undoubtedly just as true for human processing systems as it is for information processing machines. Thus, it may not be surprising that novel techniques for assessing processing speed, such as the Brinley plot (Brinley, 1965), should attract considerable interest and even controversy (e.g., Cerella, 1994; Faust, Balota, Spieler, & Ferraro, 1999; Fisk & Fisher, 1994; Myerson, Wagstaff, & Hale, 1994; Ratcliff, Spieler, & McKoon, 2000). The typical Brinley plot compares the response times (RTs) of two groups, each exposed to the same set of experimental conditions. One group's mean RTs for each condition are plotted as a function of the other group's mean RTs for the corresponding conditions. Most commonly, Brinley plots are used in meta-analyses, and this graphical technique is accompanied by analogous regression analyses (i.e., analyses in which one group's condition mean RTs are regressed on the corresponding RTs of another group). The resulting regression slopes are assumed to measure the relative processing speed of the two groups (Cerella, 1985, 1990; Cerella & Hale, 1994).

Recently, however, this interpretation of Brinley plot regression slopes has been challenged. Ratcliff and his colleagues stated that "Brinley plots are quantile–quantile (Q–Q) plots" (Ratcliff et al., 2000, p. 1), and they concluded that Brinley plot regression slopes measure relative variability, not speed. Their reasoning, however, is based on a false premise. That is, Brinley plots are *not* Q–Q plots, as we will demonstrate below. In addition, we will present converging evidence from studies of visual search, mental rotation, and memory scanning that Brinley plot regression slopes *do* measure relative processing speed.

The Brinley plot approach may be illustrated using Brinley's (1965) original data (Figure 1). The Brinley study was conducted to determine whether young and older adults were differentially affected by shifting between cognitive sets, or task switching, as it is termed today (e.g., Hartley & Little, 1999; Kramer, Hahn, & Gopher, 1999). There were nine shift conditions that required multiple-choice decisions involving task switching either within or between trials, nine analogous nonshift conditions, and three simple (checking and copying) nonshift conditions. Brinley reported that when older adult condition means were regressed on the corresponding young adult condition means, the regression slope for shift tasks appeared to be identical to the slope for nonshift tasks. Consistent with this observation, our analysis of his data revealed no significant differences between the slope and intercept parameters for the two types of tasks [both $t$s $(17) < 1.0$]. The slope of the regression line fit to all of the data suggests that, regardless of the type of task, the older adults took approximately 1.7 times as long as the young adults to process the same information.[1]

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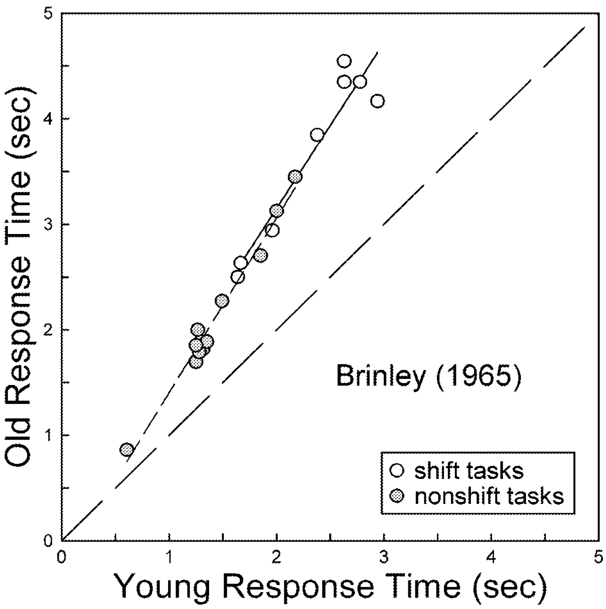



**Figure 1. Mean response time (RT) of the older adult group as a function of the mean RT of the young adult group in the corresponding experimental condition. The solid line is fit to the data from the 9 shift conditions (open circles) and the dashed line is fit to the data from the 12 nonshift conditions. If the condition mean RTs for the old and young groups were equal, the points would fall along the diagonal. Data are taken from Brinley (1965).**

Although the use of Brinley plots was pioneered by researchers studying cognitive aging (e.g., Cerella, 1985; Cerella, Poon, & Williams, 1980; Hale, Myerson, & Wagstaff, 1987), the approach is quite general, as evidenced by recent studies in the areas of cognitive development (e.g., Fry & Hale, 1996; Hale, 1990; Kail, 1991, 1993), neuropsychology (e.g., Ferraro, 1996; Kail, 1994, 1997; Myerson, Lawrence, Hale, Jenkins, & Chen, 1998; Nebes & Brady, 1992; White, Myerson, & Hale, 1997), and psychopharmacology (e.g., Maylor & Rabbitt, 1993). Brinley plots may also be applied to the performance of individuals who differ in ability (e.g., Faust et al., 1999; Hale & Jansen, 1994; Zheng, Myerson, & Hale, 2000) as well as to assess the condition of individual patients in whom some brain disorder or damage is suspected (Schatz, Hale, & Myerson, 1998). Finally, application of the Brinley plot approach is not restricted to RT measures. For example, analogous graphs have been used to compare young and older adults' memory performance (e.g., Stine & Wingfield, 1988; Verhaeghen & Marcoen, 1993). Thus, despite its origins in a highly specialized area of psychological inquiry (i.e., the study of age-related slowing), the Brinley plot approach has a wide variety of potential applications in both basic research and clinical practice.

Critics of the Brinley plot approach often claim that such plots obscure specific deficits (e.g., Bashore & Smulders, 1995; Fisk & Fisher, 1994; Perfect, 1994; Ratcliff et al., 2000). In response, proponents have argued that because any specific deficits occur against a background of general slowing, detecting them requires the use of Brinley plots and related regression techniques (e.g., Cerella, 1991, 1994; Faust et al., 1999; Myerson et al., 1994; Verhaeghen & De Meersman, 1998a, 1998b). For example, regression analyses reveal that older adults' Stroop effects are much larger than those of young adults, but they are no larger than predicted by general slowing (Verhaeghen & De Meersman, 1998b), whereas age differences in negative priming effects do not simply reflect general slowing (Verhaeghen & De Meersman, 1998a). Brinley plot analyses have also revealed several differences between task types (e.g., Goodglass, Wingfield, & Ward, 1997; Mayr & Kliegl, 1993), perhaps the most notable being the difference between verbal and visuospatial tasks (e.g., Hale & Myerson, 1996; Lima, Hale, & Myerson, 1991).

When interpreting Brinley plots, researchers generally assume that the relative processing speed of two groups can be inferred from the slope of the regression of the RTs of one group on the RTs of the other group (Cerella, 1985; Cerella & Hale, 1994). This assumption has never been systematically tested, however, and (as noted above), has recently been challenged by Ratcliff et al. (2000). In the present paper, we will present meta-analytic evidence in support of this fundamental assumption. Before doing so, however, we will address Ratcliff et al.'s argument regarding Brinley plots, Q–Q plots, and the interpretation of regression slopes and intercepts.

## Are Brinley Plots Really Q–Q Plots?

We begin by considering the following excerpt from Ratcliff et al. (2000): "The important point, that the slope of a Brinley plot is the ratio of standard deviations of older and young response times, is a fundamental reinterpretation of the Brinley plot. It means that the slope of the Brinley plot shows *nothing* about slowing of older subjects relative to young subjects. ... it is the intercept ... that shows the slowing" (Ratcliff et al., 2000, p. 3). This strong statement by Ratcliff and his colleagues raises several questions:

1. Is there a difference between Brinley plots and Q–Q plots?
2. Does the slope of a Brinley plot regression line equal the ratio of the standard deviations of older and young adult condition means?
3. Does the relation between standard deviations and slopes have anything to do with whether Brinley plots are Q–Q plots?
4. Is the intercept of a Brinley plot regression line really a measure of relative speed?

The answers to these four questions, which will be provided in the present section, will set the stage for the subsequent section, in which we will address the final and most important question:

5. Does the slope of a Brinley plot regression line measure the relative speed with which two groups process information?

It may be noted that the preceding questions presuppose a distinction between RTs and processing speed measures derived from RTs. In recognizing this distinction, we are in agreement with Ratcliff et al. (2000). Our points of disagreement, however, begin with the distinction between Brinley plots and Q–Q plots.

**Q–Q plots and Brinley plots of hypothetical data**. In their recent article, Ratcliff et al. (2000) stated that a Brinley plot may be constructed in either of two quite different ways.

> A Brinley plot is constructed either by computing the mean response times for older subjects and young subjects separately for each condition of an experiment and then plotting the means against each other or by plotting the mean response times for individual subjects against each other, with the fastest older subject's mean response time plotted against the fastest young subject's response time, and so on. (p.1)

The first of these two methods, which compares group means from corresponding conditions, is the standard way of constructing a Brinley plot. The second method, in contrast, has been used only twice in cognitive aging research (Maylor & Rabbitt, 1994; Sliwinski, Buschke, Kuslansky, Senior, & Scarisbrick, 1994). Only one of these pioneering studies (Maylor & Rabbitt, 1994) referred to the plots constructed using the second method as Brinley plots, and this study carefully used the term *Brinley plots of distributions* to distinguish the plots of rank-ordered individual means, which are properly termed Q–Q plots, from standard Brinley plots based on corresponding condition means.

As we consider the assertion that Brinley plots are Q–Q plots (Ratcliff et al., 2000), it will become clear why it is vital to distinguish between naturally occurring data pairs (such as corresponding condition means) and data pairs constructed by rank ordering. In order to maintain this distinction, we shall reserve the term *Brinley plot* for plots depicting data pairs that come from corresponding experimental conditions and use the term *Q–Q plots* for plots depicting data pairs that are constructed by rank-ordering the original values. Because these two kinds of plots (i.e., Brinley and Q–Q plots) preserve and discard different aspects of the information present in the raw data, they address different issues and bear no necessary relation to each other, although a theoretical bridge between them has been proposed (Zheng et al., 2000).

Q–Q plots represent an informal, exploratory technique whose purpose is to facilitate the process of comparing distributions (Chambers, Cleveland, Kleiner, & Tukey, 1983; Lovie & Lovie, 1991). Current uses of Q–Q plots may be traced to a seminal paper on graphical techniques by Wilk and Gnanadesikan (1968) in which they described plotting methods based on the cumulative distribution function, the mathematical function that provides the basis for computing quantiles (e.g., quartiles and percentiles). Wilk and Gnanadesikan showed that a plot of the quantiles of one distribution as a function of the corresponding quantiles of another distribution can be used not only to compare the shape of an empirical distribution with that of a theoretical distribution (e.g., the Gaussian or normal distribution), but also to compare the shapes of two empirical distributions.

Consider the following highly simplified, hypothetical example. Imagine that two groups of pilot subjects perform a single experimental task, and the first four members of one group (Group X) have mean RTs of 550, 800, 650, and 400 msec, whereas the first four members of the other group (Group Y) have mean RTs of 600, 1,100, 1,400, and 900 msec. In order to use a Q–Q plot to compare the two distributions of RTs obtained so far, one would place the RTs for each group in rank order (i.e., 400, 550, 650, and 800 for Group X, and 600, 900, 1,100, and 1,400 for Group Y), and then plot the ranked RTs for Group Y as function of the correspondingly ranked RTs for Group X (i.e., one would plot the X-Y pairs 400 and 600, 550 and 900, 650 and 1,100, 800 and 1,400).

Note that when both distributions contain equal numbers of observations, as in the present example, a Q–Q plot may depict the rank-ordered observations themselves. When the numbers of observations are unequal, however, it is necessary to calculate the corresponding quantiles for each distribution in order to construct a Q–Q plot, although one also has this option when the numbers are equal. Thus, the hypothetical data presented here could also represent the 20th, 40th, 60th, and 80th percentiles of two larger groups.

A Q–Q plot of our hypothetical data would reveal a precisely linear relation with a slope of 2.0, the ratio of the standard deviations for the two groups in the pilot study (i.e., 336, the standard deviation for Group Y, divided by 168, the standard deviation for Group X). The ratio of the standard deviations indicates that the diversity of RTs is greater for Group Y, and the linearity of the relation indicates that the two groups have distributions of the same shape. Given the small number of observations in the present example, as well as its hypothetical nature, such a conclusion is not very meaningful. In more typical cases involving larger numbers of individuals in each group, however, similarities or differences in distribution shape could have important theoretical implications in addition to their obvious implications for statistical analysis.

Now consider a second example. Two groups perform four different task conditions, and the four pairs of condition means are 400 and 600, 650 and 1,100, 550 and 900, and 800 and 1,400 for Group X and Group Y, respectively. Note that because these numbers are the same as those used in the preceding Q–Q plot example, a Brinley plot of this data will be identical to the previous Q–Q plot. Moreover, the slope of the linear relation between the RTs for the two groups will be identical to the previous slope and equal to the ratio of the standard deviations of their conditions means ($2.0 = 336/168$).

However, the relative diversity of the distributions of condition means for two groups is rarely of interest. More typically, it is the relationship between the condition means for two groups that has theoretical significance, and as Chambers et al. (1983) have suggested, scatter plots (such as the Brinley plot) of naturally occurring (unranked) data pairs may well be the single most powerful statistical tool for analyzing the relationship between two variables. Because such a plot depicts a functional relationship (albeit one subject to sampling and measurement error), the slope of the regression line is usually given the standard mathematical interpretation. That is, the slope is interpreted as the ratio of the change in $y$ to the change in $x$. In the hypothetical example just considered, within the range of the data presented, the change in Group Y's RTs is always twice the change in Group X's RTs. For example, Group Y's RTs for the first two conditions differ by 500 msec, whereas Group X's RTs for the same two conditions differ by 250 msec. This implies that Group Y is twice as sensitive to condition effects as Group X, and in real data this finding would call out for theoretical explanation.

**Q–Q plots and Brinley plots of real data**. In our hypothetical example, the slopes of the Q–Q and Brinley plots were the same because the numbers (i.e., the $x$–$y$ pairs) were themselves identical, but do a Q–Q and a Brinley plot of the same data from a real experiment have identical slopes? Consider the two graphs shown in Figure 2. Both graphs depict the condition mean RTs of young and older adult groups on eight tasks—four verbal and four visuospatial (Experiment 1, Jenkins, Myerson, Joerding, & Hale, 2000).

Despite the fact that both graphs depict the same data, the Q–Q plot (left panel) presents quite a different picture from the Brinley plot (right panel). The Brinley plot reveals domain-specific slowing (Hale & Myerson, 1996; Lima et al., 1991). That is, the older adult group was much slower on the visuospatial tasks (open symbols) than on the verbal tasks (filled symbols), whereas the young adult group had similar mean RTs on the visuospatial and verbal tasks. For example, on visuospatial and verbal tasks for which the young RT was approximately 0.75 sec, the older adult visuospatial RT was approximately 1.25 sec and their verbal RT was approximately 1.0 sec. Moreover, the domain difference increased with task difficulty (as indexed by the young adults' RTs), so that on visuospatial and verbal tasks for which the young RT was approximately 1.0 sec, the older adult visuospatial RT was more than 2.0 sec but their verbal RT was less than 1.5 sec.

The Q–Q plot, on the other hand, conceals the domain-specific nature of age-related slowing. This is because ranking the condition mean RTs for each group separately resulted, in many cases, in older adults' verbal RTs being plotted as a function of young adults' visuospatial RTs (upright triangles) and older adults' visuospatial RTs being plotted as a function of young adults' verbal RTs (inverted triangles). The Q–Q plot is orderly, although nonlinear, but that order was created by the ranking process, and is in that sense artificial. In fact, less than one-fifth of the young adult condition mean RTs were paired with older adult mean RTs from the same condition.

The results of this plotting exercise are instructive. Plotting the same data in two different ways reveals that, contrary to Ratcliff et al. (2000), a Brinley plot is *not* a Q–Q plot. This is not to say that, under special circumstances, Brinley and Q–Q plots of the same data cannot be equivalent, just that they need not be. The ranking process can, and frequently does, create new pairings of condition

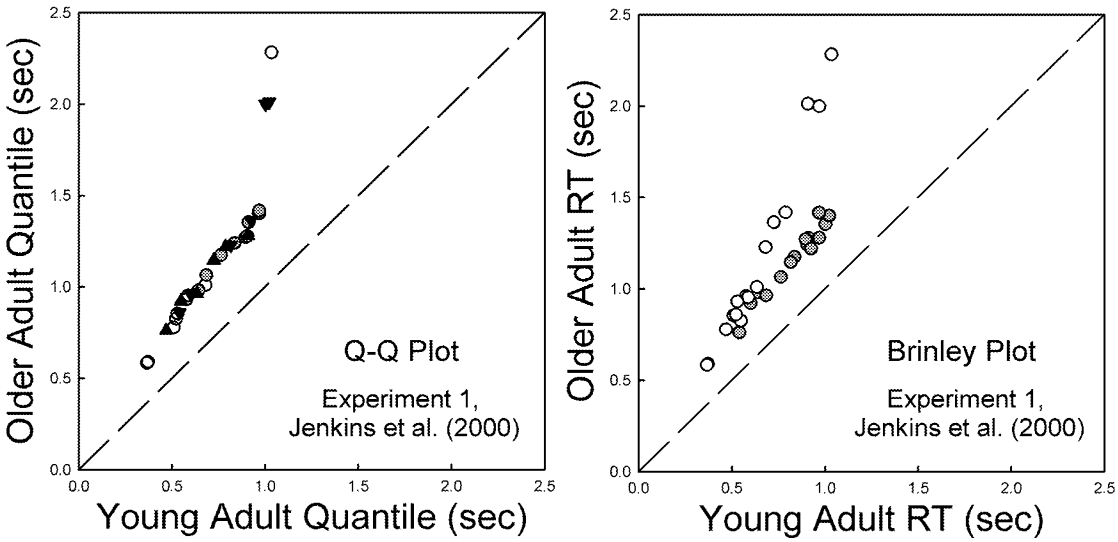



**Figure 2. Quantile–quantile (Q–Q) and Brinley plots of the data from Experiment 1 of Jenkins et al. (2000). The Q–Q plot (left panel) presents the ranked condition mean response times (RTs) for the older adult group as a function of the correspondingly ranked condition mean RTs for the young adult group. The Brinley plot of the same data (right panel) presents the condition mean RTs for the older adult group as a function of the mean RTs for the young adult group in the corresponding conditions. Open circles represent old visuospatial condition RTs plotted as a function of young visuospatial condition RTs, and filled circles represent old verbal condition RTs plotted as a function of young verbal condition RTs. Solid triangles, seen in the Q–Q plot only, represent old verbal condition RTs as a function of young visuospatial condition RTs (upright triangles) and old visuospatial condition RTs as a function of young verbal condition RTs (inverted triangles). In both plots, if the RTs for the old and young groups were equal, the points would fall along the diagonal.**

means that are without theoretical significance. In fact, most published Brinley plots probably would not be equivalent to a Q–Q plot of the same data. Brinley's (1965) original plot, to pick a famous example, is certainly not equivalent to a Q–Q plot of the same data. For example, the condition that is associated with the longest RT for older adults is not the condition associated with the longest RT for older adults (Figure 1).

**Slopes, intercepts, and linear regression**. We have seen that Brinley plots and Q–Q plots of real data may have quite different properties from plots like those presented by Ratcliff et al. (2000), which are based on hypothetical data. This raises the question of whether real data show the correspondence between regression slopes and standard deviation ratios that was predicted by Ratcliff et al. and that is observed in their hypothetical data. To answer this question, we again consider the Q–Q plot and the Brinley plot of the Jenkins et al. (2000) data depicted in Figure 2. In both cases, the observed slope was lower than the ratio of the standard deviations. The slope for the relation between corresponding quantiles was 1.74, and the slope of the Brinley plot regression line was 1.59. Both of these values are considerably lower than the value of 1.93 that, according to Ratcliff et al., would be expected based on the standard deviation of the condition means for the older adult group (0.390 sec) and the standard deviation of the condition means for the young adult group (0.202 sec).

In contrast, the slopes of the Brinley plot regression lines for the visuospatial and verbal tasks, analyzed separately, were accurately predicted by the standard deviation ratios. The slopes for separate visuospatial and verbal (Brinley plot) regression lines were 2.56 and 1.22, respectively, whereas the corresponding standard deviation ratios were 2.60 and 1.24. Taken together with the inability of the standard deviation ratio to predict the slope of the relation between young and older adult RTs from all of the conditions (i.e., the slope of the regression line for the Brinley plot as a whole), these findings raise serious questions regarding Ratcliff et al.'s (2000) interpretation of Brinley plot slopes.

What is the reason for the striking difference between the accuracy with which the standard deviation ratio predicts the slopes for two domain-specific subsets versus the (much lower) accuracy with which the standard deviation ratio predicts the slope for the whole data set? Consider Ratcliff et al.'s (2000) Equation 1. This equation provided the basis for their prediction that the slope of a Brinley plot will equal the ratio of the standard deviations of older and young RTs. In turn, this prediction provided the basis for their claim that slopes say nothing about age-related slowing (or, more generally, about the relative speed with which any two groups process information). Ratcliff et al.'s Equation 1 states that

$$Q_Y = (SD_Y / D_X)\, Q_X + M_Y - (SD_Y / D_X)\, M_X, \qquad (1)$$

where $Q$, $SD$, and $M$ represent the quantiles, standard deviations, and means of the young and older adult RT distributions which are denoted by the subscripts $X$ and $Y$, respectively.

The reason for the variations in the accuracy of predictions based on Equation 1 is that the equation is, in fact, a special case of the more general equation for regression/correlation (Cohen & Cohen, 1983). This may be seen if the regression/correlation equation is written in an analogous fashion:

$$Y = r\,(SD_Y / SD_X)\, X + M_Y - r\,(SD_Y / D_X)\, M_X, \qquad (2)$$

where $Y$ is the variable regressed on $X$ and $r$ is the correlation coefficient. Simply put, Equation 2 reveals that the predictive validity of Ratcliff et al.'s (2000) Equation 1 depends on the strength of the linear relationship between $X$ and $Y$ (as measured by $r$). In the specific case of the Jenkins et al. (2000) data (see Figure 2), the relationship between $X$ and $Y$ values is simply not as strong or as linear either for the quantile data or for condition means considered as a whole as it is for the two domain-specific subsets of the condition mean data considered separately. In general, the correspondence (or lack thereof) between standard deviations and slopes appears to be a fundamental property of estimates of linear regression/correlation and can provide no support for Ratcliff et al.'s contention that Brinley plots are Q–Q plots.

Equations 1 and 2 also help illuminate the meaning of the regression intercept. According to the general regression/correlation equation (Equation 2), the slope is equal to the product of the correlation and the ratio of the standard deviations. According to Ratcliff et al.'s (2000) Q–Q equation (Equation 1), the slope is simply equal to the ratio of the standard deviations (i.e., the strength of the correlation is implicitly assumed to be 1.0). In both equations, however, the intercept equals the difference between the mean of the $Y$ values (e.g., older adult RTs) and the product of the slope and the mean of the $X$ values (e.g., young adult RTs):

$$\text{Intercept} = M_Y - \text{Slope} \times M_X. \qquad (3)$$

Thus, from Ratcliff et al.'s perspective, the intercept measures the difference between the observed mean for the $Y$ group and the mean predicted for this group based purely on how variable they are relative to the $X$ group. If the difference in RTs were wholly attributable to relative variability, the intercept would be zero, but if there were slowing over and above that attributable to relative variability, the intercept would be positive.

The actual result observed in most Brinley plot analyses of young and older adults' RTs is that the intercept is negative. Ratcliff et al. (2000) stated that this occurs because "older subjects' means are larger than younger subjects' means, but not by too much, relative to their standard deviations" (p. 6). Although we find this statement rather vague, Ratcliff et al.'s Q–Q equation makes the mathematical meaning of the observed negative intercepts extremely clear. According to their Q–Q equation, intercepts are negative when condition mean RTs are *faster* than would be predicted on the basis of variability. If, as Ratcliff et al. contend, age-related changes in variability (as indexed by regression slopes) should be disregarded when one is evaluating speed, then, given the observed negative intercepts, one would have to conclude that older adults are actually faster than young adults. No one, including Ratcliff et al., would probably be comfortable with that conclusion. Thus, their emphasis on the intercepts of Brinley plot regression lines as the preferred measure of relative speed appears to be misplaced.

Instead, the observed negative intercepts seem to reflect the fact that the cognitive processes involved in standard experimental tasks are more affected by aging than are the sensorimotor processes (Cerella, 1985, 1990; Myerson, Hale, Wagstaf, Poon, & Smith, 1990; Zheng et al., 2000). As was the case according to Ratcliff et al.'s (2000) interpretation, the interpretation proposed by both Cerella and Myerson and his colleagues implies that older adults' RTs are faster than would be predicted on the basis of regression slopes alone (i.e., intercepts are typically negative; see Equation 3). According to Cerella and Myerson, however, this occurs because the slopes of Brinley plot regression lines reflect only cognitive slowing, whereas the RTs consist of both cognitive and sensorimotor components.

This interpretation was originally proposed by Cerella (1985) in the context of a meta-analysis of data from early cognitive aging studies that differed greatly in their sensorimotor requirements (from vocal responses to card sorting). Myerson et al. (1990) focused on the case, exemplified by more recent research on age-related slowing, in which the sensorimotor requirements are minimal (typically a button push in response to a high-contrast visual stimulus) and are fairly similar across studies. They showed that under these conditions,

$$O = m_c Y - a(m_c - m_p), \tag{4}$$

where $O$ is the condition mean RT for the older group, $Y$ is the condition mean RT for the young group, $a$ is the duration of peripheral sensorimotor processes for the young group, $m_c$ is the degree of age-related cognitive slowing, and $m_p$ is the degree of age-related peripheral slowing (see also Equation 9, Cerella, 1990).

The consequences of Equation 4 may be considered graphically and analytically. From the graphical perspective, imagine a Brinley plot for which the data contains, in addition to data from more complex task conditions, one point from a simple sensorimotor task ($X = a$, $Y = m_p a$). If the degree of sensorimotor slowing is relatively small, this sensorimotor point will lie close to the equality diagonal (i.e., the line $Y = X$). Because of the leverage exerted by this point, the Brinley plot regression line will tend to pass through it, and any line with a slope greater than 1.0 that passes through this point will tend to have a negative intercept. Moreover, the larger the slope, the more negative the intercept, as Cerella (1985, 1991) observed.

From the analytical perspective, Equation 4 reveals that when the degree of cognitive slowing is greater than the degree of sensorimotor slowing ($m_c > m_p > 1.0$), as reported by Cerella (1985), the intercept will be negative: $-a(m_c - m_p) < 0.0$. Moreover, holding the sensorimotor task requirements constant, any variation in the degree of cognitive slowing, whether between samples or between tasks, will produce a negative correlation between slopes and intercepts across studies (e.g., Cerella, 1985, 1991). This analysis may be extended to the regression of individual RTs on group mean RTs in studies examining individual differences in cognitive speed. In such cases, the present analysis correctly predicts that *slow* individuals will have slopes greater than 1.0 and *negative* intercepts, whereas *fast* individuals will have slopes less than 1.0 and *positive* intercepts (Hale & Jansen, 1994; Zheng et al., 2000).

**Questions and answers**. We have now considered each of the first four questions posed earlier. With respect to the first question, concerning whether Brinley plots are Q–Q plots, we have shown that Brinley plots and Q–Q plots are not equivalent because they convey different kinds of information. Importantly, the rank ordering that is necessary to construct a Q–Q plot of two groups' condition mean RTs will tend to alter the pairings of the condition means, potentially obscuring the phenomenon of interest—that is, the relationship between one group's performance and the performance of another group under the same conditions. It is Brinley plots, and not Q–Q plots, that reliably convey information regarding this relationship.

With respect to the question of whether standard deviation ratios predict Brinley plot regression slopes, we have shown that although the slope sometimes corresponds to the ratio of the standard deviations of the two groups' condition means, sometimes it does not correspond to this ratio—it all depends on the strength and linearity of the relationship. As to the question of whether the relationship between the slope and the standard deviation ratio tells us anything about whether or not Brinley plots are Q–Q plots, the short answer is "no." More specifically, Ratcliff et al.'s (2000) statement regarding the relation between Brinley plot slopes and standard deviation ratios turns out to be a mathematical fact about regression lines in general and has nothing to do with what type of data are described by the regression equation. To the extent that a Brinley plot shows a strong linear relationship, it will be similar to a Q–Q plot of the same data, and they will both share the properties of a straight line (which include a standard deviation ratio approximately equal to the regression slope)—all of which simply begs the question of why there is an orderly, linear relationship between condition means in the first place.

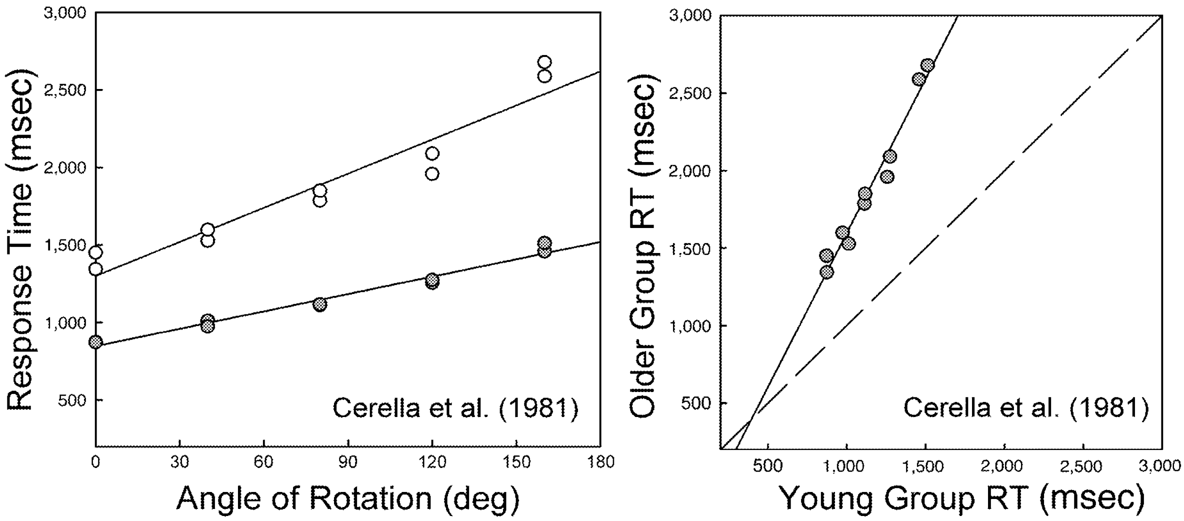
The question of whether the intercept of the Brinley plot regression line is really a measure of relative speed, as Ratcliff et al. (2000) claimed, must be seen in the theoretical context of their other claim that the slope is really a measure of relative variability. It is true that, from their perspective, the intercept might be thought of as a speed measure because it compares the overall mean RTs for two groups while effectively controlling for variability differences. We have shown, however, that this interpretation of the intercept also leads to the conclusion that older adults are really faster than young adults because the intercepts of Brinley plot regression lines are typically negative. Finally, we presented an alternative interpretation, according to which intercepts reflect differences in sensorimotor and cognitive speed, and negative intercepts occur when cognitive speed differences are greater than sensorimotor speed differences (Cerella, 1985; Myerson et al., 1990).

## Do Brinley Plot (Regression) Slopes Measure Relative Speed?

Consider what the implications would be if Ratcliff et al. (2000) were correct about Brinley plots. If Ratcliff et al. were correct it would mean that cognitive psychology's few quantitative laws would need to be radically reinterpreted. This is because Ratcliff et al.'s argument applies not just to Brinley plots, but to all other types of scatter plots as well. Consider, for example, the implications of Ratcliff et al.'s thesis for mental rotation. The slope of the relation between RT and the angle of orientation of the stimulus is usually assumed to reflect the rate of mental rotation. That is, in keeping with the standard interpretation of slopes as representing the ratio of the change in $Y$ (e.g., response times, in milliseconds) to the change in $X$ (e.g., angle in degrees), the mental rotation slope is assumed to indicate the number of milliseconds it takes to mentally rotate an image of the stimulus by 1° (e.g., Shepard & Cooper, 1986). In contrast, Ratcliff et al.'s argument, as applied to the mental rotation plot, implies that the slope of the relation between RT and stimulus orientation shows *nothing* about the rate of mental rotation but is simply the ratio of standard deviations of response times and angles. Finally, taken to its logical conclusion, their argument implies that rotation rate is actually indicated by the intercept of the regression of RT on stimulus orientation rather than the slope.

It is true, of course, for mental rotation functions (as it is for any approximately linear function) that the slope will reflect, in part, the ratio of the standard deviations of the $X$ and $Y$ variables. As we have seen, however, the general regression correlation equation (Equation 2) clearly implies that the correspondence between slope and standard deviation ratio is the property of any highly orderly linear relationship and has no theoretical significance. Today, most cognitive researchers would probably accept the proposition that the slope of the mental rotation function measures the amount of time it takes to accomplish a specified amount of processing, as Shepard originally proposed (e.g., Corballis, 1988; Jolicœur & Humphrey, 1998; for a review, see Shepard & Cooper, 1986). It should be possible, therefore, to use the mental rotation rates of two groups to predict the slope of a Brinley plot regression line fit to their data, if, as has been suggested (e.g., Cerella, 1985; Cerella & Hale, 1994), the Brinley plot slope indicates the relative speed of two groups.

Consider Figure 3, which replots the mental rotation data for young and older adults from a study by Cerella, DiCara, Williams, and Bowles (1981). The left panel presents the data in standard form: Each group's mean RTs are plotted as a function of stimulus angle. The right panel shows a Brinley plot of the same data: The older adult group's RTs at each angle are plotted as a function of the corresponding young adult group's RTs. Note that the slope of the regression of older adults RTs on those of young adults and the ratio of their mental rotation rates are nearly equivalent. On average, older adults took 7.33 msec to rotate an image 1° compared with the 3.74 msec that it




| Rate of rotation | Young | Old |
|---|---|---|
| Slope (msec/deg) | 3.74 | 7.33 |

| Speed Ratio | Brinley Slope |
|---|---|
| 1.96 | 1.99 |

**Figure 3. Two plots of the mental rotation response times (RTs) from Cerella et al. (1981). The left panel presents the condition mean RTs for the older adult group (open circles) and young adult group (filled circles) as a function of the number of degrees by which the orientation of the stimulus differed from upright. The right panel shows a Brinley plot of the same data. Note that the slope of the Brinley plot regression line is approximately equal to the speed ratio (i.e., the number of milliseconds per degree for the older adults divided by the number of milliseconds per degree for the young adults) calculated on the basis of the slopes of the mental rotation functions (i.e., the regression lines shown in the left panel).**

took young adults. This is consistent with the relative speed interpretation of the slope of the Brinley plot regression line, which implies that the older adults took approximately twice as long as the young adults to perform the same processing operations.

The preceding analysis suggests a more general empirical test of what is, as Ratcliff et al. (2000) pointed out, the fundamental assumption underlying the interpretation of Brinley plots. Surprisingly, this assumption (i.e., that the regression slope indicates relative speed) has not been systematically tested before, although Cerella (1991, 1994) has demonstrated how such a test would work in specific cases. That is, by focusing on tasks where it is possible to measure the speed with which each of two groups performs a relatively well defined cognitive process (e.g., mental rotation, visual search, and short-term memory scanning), it should be possible to determine whether or not Brinley plot regression slopes accurately reflect these groups' relative processing speed.[2]

Recall that when we listed the questions raised by Ratcliff et al.'s (2000) claim that Brinley plots are Q–Q plots, this issue provided the basis for the last, and potentially most important, question: What does the slope of a Brinley plot regression line tell us about the relative processing speed of the groups being compared? Although the Cerella et al. (1981) data are consistent with the relative speed interpretation of Brinley plot regression slopes, these are data from only one study, specifically selected to illustrate the point we were making. Because of the fundamental importance of this issue, a fuller, more rigorous evaluation of exactly how the relative processing speed of two groups relates to the slope of the regression of one group's condition mean RTs on the corresponding RTs of the other group is needed. We recently conducted such an evaluation, and the results are described in the next section.

**Sliwinski and Hall's (1998) meta-analysis**. The controversial nature of Brinley plots would seem to set a high bar for anyone wishing to establish the validity of this approach. Accordingly, rather than select a set of studies ourselves (thereby possibly raising questions regarding our selection criteria), we chose to analyze a data set that had been assembled by other researchers for a previous meta-analysis (Sliwinski & Hall, 1998). This data set had the advantage that it contains studies whose results were consistent with a general slowing hypothesis as well as studies whose results, as Sliwinski and Hall demonstrated, were not consistent with this hypothesis. This allowed us to assess whether Brinley plot regression slopes measured relative processing speed in studies whose results were not consistent with general slowing as accurately as they measured relative processing speed in studies whose results were consistent with general slowing.

Sliwinski and Hall's (1998) meta-analysis was motivated by questions concerning the validity of some of the meta-analytic methods previously used to test the general slowing hypothesis. In particular, they questioned the use of simple regression models in meta-analyses where the data set consisted of the results from a number of studies, each of which often contributed multiple data points. Sliwinski and Hall argued that because of the nested structure of such data, it should be analyzed using hierarchical linear models rather than ordinary least squares techniques, and they conducted their own meta-analysis in order to compare the two approaches.

For purposes of their statistical approach, Sliwinski and Hall (1998) chose to examine three relatively well defined cognitive processes: mental rotation, visual search, and short-term memory scanning. Studies of these processes typically vary one dimension of the task (i.e., stimulus orientation, number of elements in the display, and the size of the memory set), and this property made it possible for Sliwinski and Hall to estimate the slope of the regression of older adult RTs on young RTs for individual experiments. More importantly for present purposes, however, this property also makes it possible to obtain separate estimates of the speed with which each of the groups in a particular experiment executes a specific cognitive operation (e.g., mental rotation).

The data set assembled by Sliwinski and Hall (1998) includes six studies of mental rotation, seven studies of visual search, and nine studies of memory scanning. Sliwinski and Hall reported that, consistent with their statistical argument, ordinary least squares regression yielded no significant differences between the three types of tasks, whereas a test based on hierarchical linear models did yield significant differences. The latter technique yielded an estimated slope for memory scanning tasks of 1.25, which differed significantly from the slopes for the other two types of tasks, visual search and mental rotation. In fact, the estimated mean slopes for these latter two tasks were not merely statistically equivalent, they were nearly identical: 1.95 for mental rotation versus 1.97 for visual search. The difference between memory scanning and the other two tasks may reflect the difference in slowing between the verbal and visuospatial domains (Hale & Myerson, 1996; Jenkins et al., 2000; Lima et al., 1991). Consistent with this interpretation, all but two of the memory scanning experiments required subjects to remember either words or the names of letters and digits, and the one memory scanning experiment in which the degree of slowing was similar to that for mental rotation and visual search involved a memory set consisting of three-dimensional objects (Puglisi & Morrell, 1986).

As may be seen in Figure 4, however, the difference in mean regression slope is not the only difference between the memory scanning data and the data from the two visuospatial tasks. Not only are the regression lines for the memory scanning experiments different from those for the other two tasks—they are also obviously much more varied. The reasons for this are obscure, although questions have been raised regarding the reliability of memory scanning measures (Becker et al., 1995). In contrast, slope measures for other information processing slopes (e.g., mental rotation) have been shown to be highly reliable (Damos & Carter, 1995). In any case, the lack of consistency in memory scanning slopes suggests that it may be premature to draw any conclusions regarding the effect of aging on memory scanning rates.

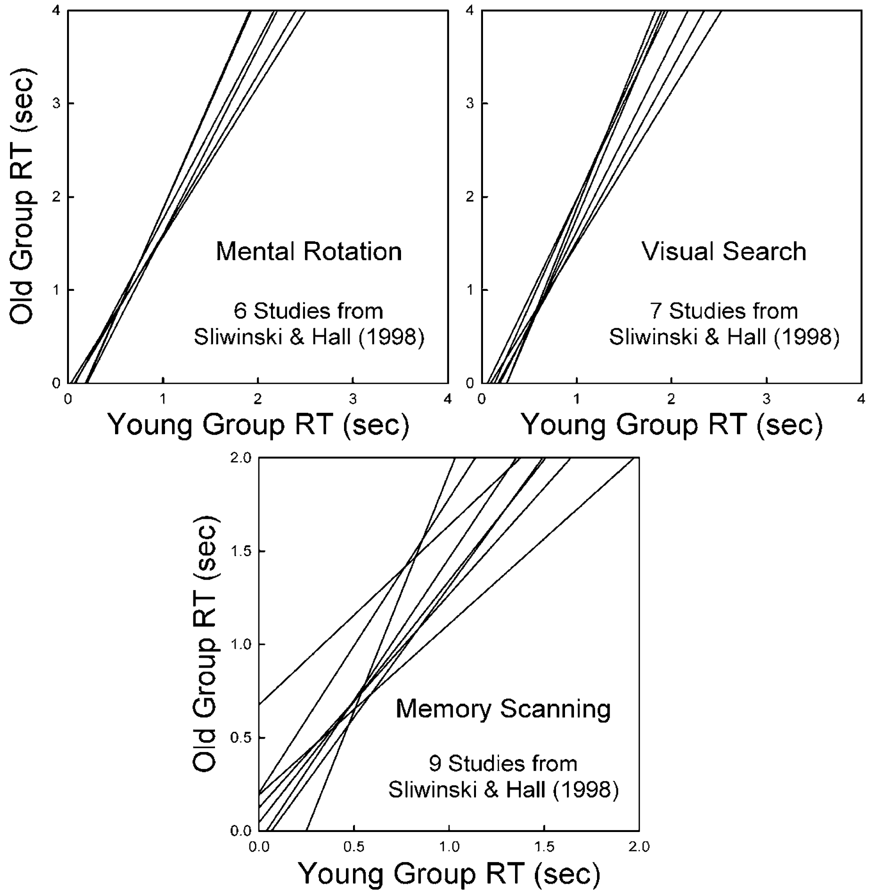



**Figure 4. Brinley plots showing the regression lines for the mental rotation, visual search, and memory scanning studies included in the Sliwinski and Hall (1998) data set. The regression lines for each study are extended to the axes to facilitate comparison. Note that the axis scales used for plots of the memory scanning studies (0–2 sec) differ from those used for the mental rotation and visual search studies (0–4 sec) because of the much shorter RTs observed in memory scanning experiments.**

Regardless of what the correct theoretical interpretation turns out to be, these findings (i.e., that mental rotation and visual search slopes differ from memory scanning slopes, which tend to differ among themselves) are advantageous for present purposes. They indicate that the Sliwinski and Hall (1998) data set contains examples of general slowing within at least one (i.e., the visuospatial) domain as well as possible examples of task-specific and even study-specific differences in the degree of age-related slowing (i.e., the memory scanning data). This is important because in order to assess whether Brinley plots and regression analyses provide an objective, atheoretical approach to measuring relative speed, we need to be able to test whether they provide reliable results (i.e., results consistent with those obtained using a separate, accepted methodology) regardless of whether those results are consistent or inconsistent with the general slowing hypothesis. If Brinley plot regression analyses cannot reveal exceptions to general slowing where such exceptions are known to exist, then this approach cannot be used to assess the validity of general slowing.

**Further analyses of Sliwinski and Hall's (1998) data set**. For present purposes, our primary interest in the Sliwinski and Hall (1998) data set is in what it can tell us about the interpretation of Brinley plot regression slopes. To address this issue, we performed three regression analyses on the data from each of the 22 studies assembled by Sliwinski and Hall (see their Table 1 for details). More specifically, we regressed the mean older adult RTs for each condition on the corresponding mean young adult RTs to obtain the Brinley plot regression slope, and we regressed the condition mean RTs for each age group separately on the independent variable (e.g., memory set size). The latter two regression analyses yielded a slope for each age group corresponding to the speed with which they performed a particular cognitive process (e.g., for memory scanning, the number of milliseconds per item in the memory set); these results were then used to calculate a

**Table 1**
**Regression Intercepts, Slopes, and $r^2$s for Studies From Sliwinski and Hall (1998)**

| | Young | | | Old | | |
|---|---|---|---|---|---|---|
| Task and Slope/Study | Intercept | Slope | $r^2$ | Intercept | Slope | $r^2$ |
| Mental Rotation (msec per degree) | | | | | | |
| Berg et al. (1982) | 961.6 | 7.48 | .961 | 1,678.4 | 14.39 | .961 |
| Cerella et al. (1981) | 847.5 | 3.74 | .976 | 1,300.4 | 7.33 | .918 |
| Dror & Kosslyn (1995) | 1,492.0 | 5.96 | .975 | 2,370.0 | 9.56 | .953 |
| Hale et al. (1991) | 673.7 | 2.95 | .983 | 1,032.0 | 5.11 | .995 |
| Hale et al. (1995) | 629.5 | 2.71 | .969 | 995.4 | 6.60 | .982 |
| Hertzog et al. (1993) | 711.0 | 5.38 | .996 | 1,209.2 | 12.30 | .982 |
| Visual Search (msec per item searched) | | | | | | |
| Foster et al. (1995) | 456.6 | 20.8 | .980 | 455.7 | 51.5 | .976 |
| Hale et al. (1995) | 530.8 | 21.3 | .971 | 672.0 | 54.8 | .984 |
| Madden (1986) | 391.0 | 130.0 | .999 | 490.3 | 212.5 | .965 |
| Plude et al. (1983) | 342.8 | 143.3 | .652 | 574.5 | 307.4 | .672 |
| Plude & Hoyer (1986) | 363.3 | 58.3 | .977 | 514.0 | 132.8 | .956 |
| Plude & Doussard-Roosevelt (1989) | 595.6 | 26.2 | .992 | 814.3 | 52.7 | .981 |
| Zacks & Zacks (1993) | 440.3 | 23.3 | .913 | 471.4 | 44.7 | .962 |
| Memory Scanning (msec per memory item) | | | | | | |
| Cerella et al. (1986) | 492.5 | 52.5 | 1.000 | 686.7 | 60.0 | .972 |
| Coyne et al. (1986) | 487.3 | 31.9 | .982 | 851.2 | 30.1 | .795 |
| Fisk et al. (1990) | 375.0 | 136.0 | .488 | 571.3 | 110.7 | .368 |
| Madden (1982) | 463.7 | 46.7 | .845 | 566.7 | 61.3 | .686 |
| Menich & Baron (1990) | 490.7 | 126.5 | .901 | 668.7 | 170.0 | .958 |
| Puglisi & Morrell (1986) | 535.0 | 50.0 | .971 | 717.5 | 132.5 | .999 |
| Salthouse & Somberg (1982) | 726.7 | 63.3 | 1.000 | 1,350.0 | 100.0 | 1.000 |
| Salthouse (1994) | 674.5 | 71.8 | .976 | 1,327.5 | 68.0 | .935 |
| Strayer & Kramer (1994) | 353.7 | 27.0 | .918 | 484.7 | 39.6 | .833 |

*processing speed ratio*, defined as the ratio of the regression slopes for the two groups. This ratio indicates how much time it took the older adult group relative to the time it took the young adult group to perform the same cognitive operation.

A few other details of our analytic procedures should be noted. For mental rotation studies, we did not distinguish between clockwise and counterclockwise rotations where they were reported separately but used the deviation of the stimulus from upright as the independent variable. For visual search studies, we used the mean number of items searched as the independent variable. On target-absent trials, the number of items searched was assumed to be equal to the set size; on target-present trials, the mean number of items searched was assumed to be equal to half of the set size plus 0.5 (e.g., when set size was three, it was assumed that subjects were equally likely to search one, two, or three items before finding the target, so that on average, subjects searched 2 items). The results for the regression of RT on the independent variable are presented in Table 1, and the speed ratios as well as the results for the Brinley plot analyses are presented in Table 2.

Recall that the critical question motivating these analyses is whether the slope of the Brinley plot regression line really measures the degree of cognitive slowing: that is, is the slope equivalent to the ratio of the rates at which different groups perform specific cognitive processes? The answer to this question is apparent from Figure 5. The left panel compares the mean Brinley plot slopes with the mean speed ratio for each task. As may be seen, both the mean Brinley plot regression slope for memory scanning studies and the mean ratio of memory scanning speeds were considerably lower than the corresponding measures for mental rotation and visual search. The correspondence between Brinley slopes and speed ratios is nevertheless extremely good for each of the cognitive processes under consideration (i.e., memory scanning, mental rotation, and visual search).

The right panel examines the correspondence between the Brinley plot regression slope and the processing speed ratio for the two age groups on a study-by-study basis. As may be seen, the correspondence is very good ($r = .996$), and there is little tendency for the speed ratio to be higher or lower than expected based on the slope of the Brinley plot regression line. These results suggest that, regardless of whether the data are consistent (as in the case of mental rotation and visual search) or inconsistent (as in the case of memory scanning) with a single age-related slowing factor, Brinley plot slopes can still provide a good index of relative processing speed.

**Converging evidence**. Our analyses of the Sliwinski and Hall (1998) data set have both theoretical and methodological implications. Of these, the methodological implications may have primacy here because a major goal of our analyses was to evaluate the assumption that Brinley plot regression slopes measure relative processing speed. Moreover, the theoretical implications of our analyses depend on establishing the validity of this assumption. Importantly, the results of the present analyses indicate that for young and older adults, the slope of a Brinley plot re-

**Table 2**
**Brinley Plot Regression Parameters, $r^2$s, and Speed Ratios for Studies From Sliwinski and Hall (1998)**

| Task/Study | Intercept | Slope | $r^2$ | Speed Ratio |
|---|---|---|---|---|
| Mental Rotation | | | | |
| Berg et al. (1982) | −146.6 | 1.908 | .986 | 1.923 |
| Cerella et al. (1981) | −395.8 | 1.991 | .968 | 1.963 |
| Dror & Kosslyn (1995) | −46.6 | 1.615 | .991 | 1.605 |
| Hale et al. (1991) | −116.9 | 1.713 | .991 | 1.731 |
| Hale et al. (1995) | −442.9 | 2.318 | .921 | 2.431 |
| Hertzog et al. (1993) | −418.2 | 2.287 | .988 | 2.284 |
| Visual Search | | | | |
| Foster et al. (1995) | −638.0 | 2.407 | .939 | 2.479 |
| Hale et al. (1995) | −677.7 | 2.554 | .997 | 2.574 |
| Madden (1986) | −154.3 | 1.643 | .976 | 1.635 |
| Plude et al. (1983) | −130.7 | 2.103 | .990 | 2.145 |
| Plude & Hoyer (1986) | −310.8 | 2.273 | .972 | 2.280 |
| Plude & Doussard-Roosevelt (1989) | −391.5 | 2.020 | .997 | 2.012 |
| Zacks & Zacks (1993) | −317.2 | 1.840 | .967 | 1.920 |
| Memory Scanning | | | | |
| Cerella et al. (1986) | 123.8 | 1.143 | .972 | 1.143 |
| Coyne et al. (1986) | 430.2 | 0.877 | .702 | 0.941 |
| Fisk et al. (1990) | −194.0 | 0.915 | .952 | 0.814 |
| Madden (1982) | −92.1 | 1.402 | .930 | 1.310 |
| Menich & Baron (1990) | 45.1 | 1.296 | .988 | 1.344 |
| Puglisi & Morrell (1986) | −637.4 | 2.558 | .959 | 2.650 |
| Salthouse & Somberg (1982) | 202.6 | 1.579 | 1.000 | 1.579 |
| Salthouse (1994) | 675.6 | 0.962 | .989 | 0.947 |
| Strayer & Kramer (1994) | −59.6 | 1.522 | .976 | 1.468 |

gression line provides a reliable estimate of the relative speed of processes such as visual search, mental rotation, and memory scanning.

Moreover, this reliability does not depend on whether slopes are relatively uniform, as predicted by general slowing. In fact, it is only because the Brinley plot approach is objective and atheoretical, and applies to data regardless of whether they are consistent with general slowing (i.e., visual search and mental rotation RTs) or not (i.e., memory scanning RTs), that Brinley plot regression slopes have the potential to provide support for general slowing or for any other theoretical position. In fact, the present analyses, both those using the Brinley plot approach and (where appropriate) those examining speed ratios for specific cognitive processes, provide converging evidence of general age-related slowing in the visuospatial domain. More specifically, normal aging appears to produce equivalent slowing of two quite different visuospatial processes: mental rotation and visual search.[3]

The findings with respect to memory scanning, however, appear to be more complicated. The present analyses of Brinley plot regression slopes and processing speed ratios replicate Sliwinski and Hall's (1998) finding that, on average, performance on memory scanning tasks appears to be less age sensitive than performance on visual search or mental rotation tasks. However, the diversity of outcomes from memory scanning experiments raises the question of whether the experiments on memory scanning are all examining the same basic process. Until the factors responsible for the diversity of outcomes are identified and understood, any attempt to quantify the effect of aging on memory scanning may be premature. For the present, the primary significance of the memory scanning results may be that they demonstrate the evenhandedness of the Brinley plot approach and show that this approach is as capable of revealing exceptions to general slowing as it is of providing supporting evidence.

## General Discussion

Ratcliff et al. (2000) suggested that age differences in time–accuracy tradeoffs, rather than the effect of age on processing speed, might underlie the well-established finding that older adults' RTs are slower than those of young adults (for meta-analytic reviews, see Cerella, 1985, 1990; Cerella & Hale, 1994; Hale et al., 1987; Lima et al., 1991). The problem with this suggestion is that age differences in time–accuracy tradeoffs have been extensively researched and found wanting as a general explanation for age differences in RTs (for a quantitative review, see Cerella, 1990). A number of more recent experiments (two of which were included in the Sliwinski et al., 1998, meta-analysis) have also addressed this issue.

In one of the experiments, Hertzog, Vernon, and Rypma (1993) gave young and older adults instructions for a mental rotation RT task that emphasized speed, accuracy, or both (neutral instructions). Interestingly, accuracy was most nearly equivalent under standard, neutral instructions (92.7% for young adults and 90.8% for older adults). Under all three kinds of instructions, older adults rotated images at least twice as slowly as young adults (relative rotation speeds ranged from 2.01 to 2.47).

In another experiment, Zacks and Zacks (1993, Experiment 1) used a forced-choice staircase procedure to determine threshold durations for visual search specifically

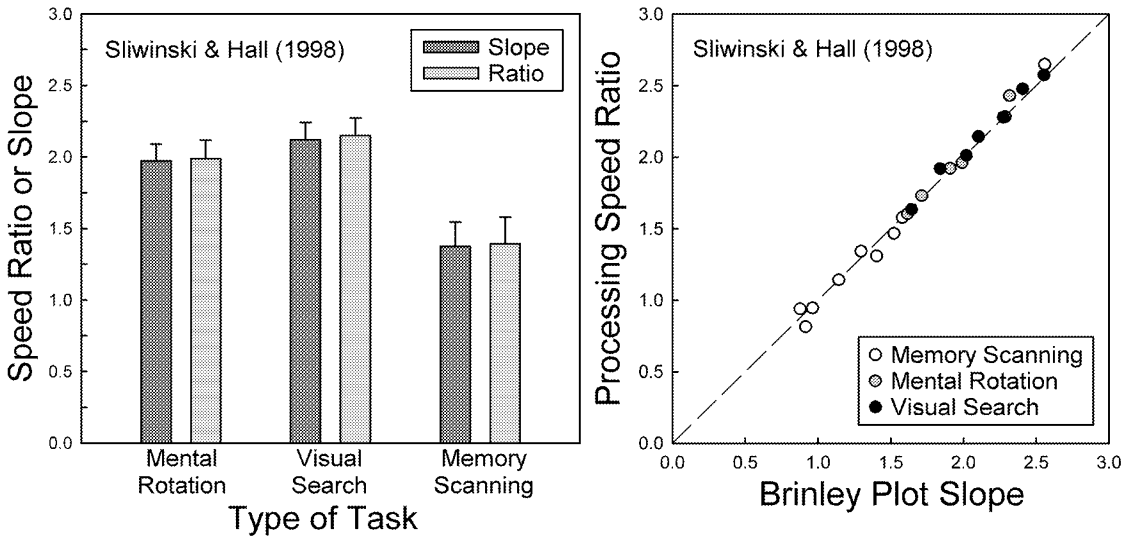



**Figure 5. Correspondence between the slopes of the Brinley plot regression lines and speed ratios calculated for the 22 studies in the Sliwinski and Hall (1998) data set. The left panel compares the mean Brinley regression slopes with the mean speed ratio, averaged across all studies that used a particular type of task (i.e., mental rotation, visual search, or memory scanning); error bars represent the standard errors. The right panel plots the processing speed ratio for each study as a function of the Brinley plot regression slope for the same study. A speed ratio equal to the corresponding Brinley regression slope is represented by a point on the (dashed) diagonal.**

to preclude the possibility of age differences in time–accuracy tradeoffs. Using this procedure, they found that older adults took 1.90 times as long per item as young adults. These results are comparable to their results for the same subjects obtained using standard RT techniques (1.94 times as long per item for older adults as for young adults) and are similar to our estimate of a 1.84 slowing factor for the Zacks and Zacks data estimated on the basis of the slope of the Brinley plot regression line (Table 2).

Three studies conducted by Mayr and his colleagues lead to similar conclusions regarding age-related differences in the speed of visual search. Importantly, these studies used a variety of measures and analytic techniques, including (1) stimulus-duration threshold measures like those of Zacks and Zacks (1993), (2) the ratio of the rate parameters of time–accuracy tradeoff functions (Mayr, Kliegl, & Krampe, 1994, 1996), and (3) the slope of a Brinley plot regression based on young and older adults' mean exposure times at different levels of accuracy and with different numbers of objects (Mayr & Kliegl, 1993). Note that, as in the study by Zacks and Zacks, the studies by Mayr and his colleagues used forced-choice procedures in which exposure time was experimentally manipulated, thereby circumventing interpretation problems caused by possible age differences in time–accuracy tradeoff. In all cases, the estimates of age-related slowing of visual search (which ranged from 1.88 to 1.97) correspond closely to the Brinley plot regression slope (2.02) and the hierarchical regression slope (1.98) for the young and older adults' visual search RTs reported by Sliwinski and Hall (1998).

We do not mean to suggest that age-related differences in time–accuracy tradeoff never occur, either naturally or in response to instructional manipulations, nor do we mean to suggest that they may not be a problem in specific studies. However, the correspondence between the findings of Brinley plot analyses of RT data and analyses of stimulus-duration thresholds determined with forced-choice procedures, taken together with years of research on this issue, strongly suggests that age differences in time–accuracy tradeoffs are not typically responsible for the age-related slowing reflected in Brinley plot regression slopes.

We would like to conclude by noting that we agree with Ratcliff et al. (2000) that one needs to distinguish between RTs and processing speed measures derived from RTs. For example, just because an older adult group's mean RT on a particular task is twice the mean RT for a young group does not mean that the older group processes information twice as slowly. This, in fact, is the reason why many researchers use Brinley plots and regression analysis as a basis for estimating the degree to which processing speed slows with age, rather than simply examining the ratio of RTs.

Ratcliff et al. (2000) recently challenged the continued use of Brinley plots for such purposes on the basis of their assertion that Brinley plots are equivalent to Q–Q plots. In contrast, we have argued that these two types of plots represent two quite different approaches to graphical analysis. Accordingly, we showed that Brinley plots and Q–Q plots are not equivalent because they convey different kinds of information. Importantly, the rank ordering that is necessary to construct a Q–Q plot of two groups' condition mean RTs tends to alter the pairings of condition means, thereby potentially obscuring the phenomenon of interest—the relationship between one group's performance and the performance of another group under the same conditions.

Clarification of this issue, however, was merely a prerequisite to testing the fundamental assumption underlying interpretation of the results of Brinley plot analyses. To address this issue directly, we conducted a meta-analysis that compared Brinley plot regression slopes with other measures of relative processing speed based on more traditional speed indices. Specifically, we compared Brinley plot slopes with the ratios of young and older adults' rates of mental rotation, visual search, and memory scanning. The results of our meta-analysis strongly support the hypothesis that Brinley plot regression slopes measure relative processing speed.

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## NOTES

1. This estimate is based on the slope (1.67) of the regression line for response times (RTs). Calculating the slope (1.69) of the regression for processing times (where processing time is calculated as the observed response time minus the sensory/motor time measured in a separate condition) leads to the same conclusion. Note that because the Brinley plot regression line has a negative intercept ($-250$ msec), the slope does not equal the ratio of the mean RTs for the two groups (1.53). Such negative intercepts are characteristic of cognitive aging data, and their interpretation is discussed in the following section (see "*Slopes, intercepts, and linear regression*"). Although Brinley plots typically reveal linear relationships between condition mean RTs, over a broader range of RTs the relationship may be described by a nonlinear function (e.g., Cerella, 1990; Hale, Myerson, & Wagstaff, 1987; Myerson, Hale, Wagstaff, Poon, & Smith, 1990). Under these conditions, relative processing speed corresponds to the derivative of the nonlinear function (i.e., the slope of a tangent).

2. In mathematical terms, the Brinley plot regression line may be considered to be the path of two parametric equations, one for each group, that are both functions of the same parameter. This parameter may be the independent variable, as in the cases under present consideration, or a more general construct such as processing load or task complexity (e.g., Cerella, 1994; Hale et al., 1987; Myerson et al., 1990). For hypothetical (error-free) data, the path may follow directly from the parametric representation. As we have just seen in our consideration of slopes and standard deviation ratios, however, real data may diverge from what is predicted in mathematically ideal cases; hence the need for empirical tests like that undertaken here.

3. In addition to specific processes (i.e., mental rotation, visual search, and memory scanning), all of these tasks have some cognitive processes in common (e.g., pattern recognition and decision making). These common processes appear to slow by age to the same extent as visual search and mental rotation processes. To determine the duration of these common processes, we estimated RTs for zero degrees of "mental rotation" and "searching" or "scanning" of a single memory item and regressed the estimates for older adults on the estimates for young adults. The slope of the regression line was 1.79, which is statistically equivalent to the slope of 1.83 for the mental rotation and visual search RTs [$t(87) < 1.0$].

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