



SPEED-ACCURACY TRADEOFF AND INFORMATION PROCESSING DYNAMICS*

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For a long time, it has been known that one can tradeoff accuracy for speed in (presumably) any task. The range over which one can obtain substantial speed-accuracy tradeoff varies from 150 msec in some very simple perceptual tasks to 1,000 msec in some recognition memory tasks and presumably even longer in more complex cognitive tasks. Obtaining an entire speed-accuracy tradeoff function provides much greater knowledge concerning information processing dynamics than is obtained by a reaction-time experiment, which yields the equivalent of a single point on this function. For this and other reasons, speed-accuracy tradeoff studies are often preferable to reaction-time studies of the dynamics of perceptual, memory, and cognitive processes. Methods of obtaining speed-accuracy tradeoff functions include: instructions, payoffs, deadlines, bands, response signals* (with blocked and mixed designs), and partitioning of reaction time. A combination of the mixed-design signal method supplemented by partitioning of reaction times appears to be the optimal method.

The basic fact that one can tradeoff accuracy for speed over some range of response times has been known for a very long time (e.g., Garret 1922; Hick 1952; Woodworth 1899). In the Garrett and Woodworth studies, the emphasis was on speed-accuracy tradeoff in a movement response measured on a continuous scale, rather than on speed-accuracy tradeoff in a discrete choice response. Hick employed a speed-accuracy tradeoff method as an additional way to test his theory of the relationship between choice reaction time and the log of the number of alternative stimuli, taking the fact of speed-accuracy tradeoff pretty much for granted. There was some confusion, particularly in

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Garrett (1922) between the time of exposure to information (brief presentation of stimuli to be judged) and processing time (forcing quick responses). However, it seems clear that the basic principle of speed-accuracy tradeoff has been known to at least some psychologists for a long time. Nevertheless, systematic work on the phenomenon of speed-accuracy tradeoff only began in the middle 60's largely due to work at the University of Michigan (e.g., Fitts 1966; Pachella and Pew 1968), but there were studies of speed-accuracy tradeoff about the same time at other places (e.g., Howell and Kreidler 1963, 1964; Ollman 1966; Schouten and Bekker 1967). To my knowledge, the first published studies that actually plotted accuracy as a function of response time, were Ollman (1966) and Schouten and Bekker (1967). Earlier studies and a number of more recent studies have plotted both accuracy and response time separately as functions of some variable, with the speed-accuracy condition as a parameter (e.g., 'speed' instructions vs 'accuracy' instructions).

Since its invention, the speed-accuracy tradeoff (SAT) function has been employed in the analysis of an increasing variety of tasks. However, it is fair to say that the area of speed-accuracy tradeoff is still a special field of its own, the province of a few investigators, with little appreciation that the speed-accuracy tradeoff experiment and the SAT function have great potential to advance all areas of cognitive psychology. It will be argued in the present paper that the speed-accuracy tradeoff method is so superior to the traditional reaction time method, that many psychologists interested in studying the dynamics of information processing in perceptual, memory, performance, psycholinguistic, and other cognitive tasks, ought, in many instances, to do speed-accuracy tradeoff studies instead of reaction time studies. Obviously, this is a strong claim. No matter how correct the claim might be or how convincing the arguments given in the present paper, the change from reaction time studies to speed-accuracy tradeoff studies will not come overnight. The change is too sweeping and the vested interests are too great to achieve instant change. However, the case for speed-accuracy tradeoff as against reaction time is so strong that this case needs to be presented as forcefully as possible to all cognitive psychologists. This is the major purpose of the present paper.

Methods of obtaining SAT functions

An SAT function is a plot of some measure of the accuracy of a response as a function of the time taken to make that response. Obviously, there are many possible measures of accuracy, even restricting oneself to discrete choice responses. One might choose probability-correct, odds, (probability-correct/probability-error), d' , $(d')^2$, information transmitted, etc. Furthermore, one can apply any transformation to any of these accuracy measures such as taking the log, squaring, some linear transformation, etc. The time variable might also be transformed. Finally, there are a variety of experimental methods for obtaining speed-accuracy tradeoff functions that are completely orthogonal to the analytic choices for the speed and accuracy scales.

At present, there appear to be six basic methods of obtaining a speed-accuracy tradeoff function: instructions, payoffs, deadlines, time bands, response signals, and partitioning of reaction times. No matter what method is used, the goal is to obtain a measurement of accuracy at each of a large number of response times as shown in fig. 1.

To make matters more concrete, let us imagine that the task of the subject is to make a 'yes-no' decision regarding whether a test item was or was not a member of some set of items presented previously in the experiment. On the test trial, an item is presented, and the subject (by one means or another) is induced to respond at some time following the

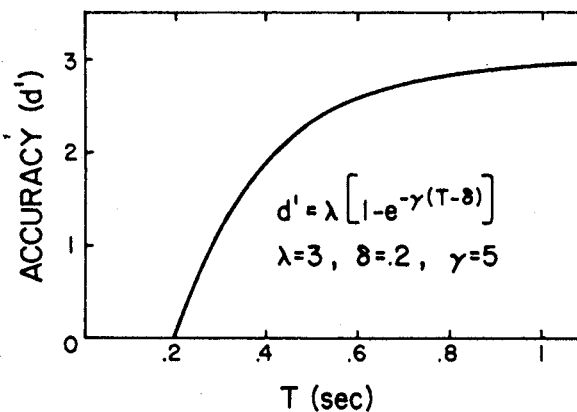


Fig. 1. Hypothetical speed-accuracy tradeoff function having the form of an exponential approach to a limit with a time intercept of $\delta = 200$ msec, a rate of $\gamma = 5$, and an accuracy asymptote of $\lambda = 3$.

onset of the test item. The time between the onset of the test item and the response is the X-axis in fig. 1. Some measure of the accuracy with which the subject makes the recognition memory decision is the Y-axis.

Several features of the hypothetical speed-accuracy tradeoff function shown in fig. 1 are worthy of note: First, there is an initial period of time following the onset of the test item (between 0 and 200 msec in fig. 1) during which the accuracy of responding is at chance. The time at which accuracy begins to rise above chance may be called the intercept (δ) of the SAT function. In fig. 1, $\delta = 200$ msec. Second, there is an asymptotic level of accuracy which is approached at relatively long reaction times. Beyond a certain amount of time, no amount of additional processing time will substantially improve the accuracy of the response. This asymptotic level of accuracy need not represent perfect performance. It may be substantially below that level, due to limitations other than processing time. The *asymptote* (λ) in fig. 1 is 3. Third, the SAT function has a certain mathematical form, such as the exponential approach to a limit shown in fig. 1 ($d' = \lambda [1 - e^{-\gamma(T-\delta)}]$). At this point, no one knows the correct mathematical form for the speed-accuracy tradeoff function for any cognitive process, so the exponential approach to a limit shown in fig. 1 should be taken solely as an example. Fourth, no matter what the mathematical form of the SAT function, there will be a parameter for the *rate* (γ) of increase in accuracy as a function of processing time. For the exponential approach to a limit shown in fig. 1, $\gamma = 5$.

Although no one knows the correct mathematical form for speed-accuracy tradeoffs under any conditions, almost everyone would agree that such functions must have an intercept parameter and a slope parameter. Some investigators have plotted SAT functions with a dependent variable chosen in such a way as to produce an SAT function that consists of a straight line with only two parameters: intercept and rate. This approach is feasible for responses that approach perfect accuracy with unlimited processing time, but there would seem to be no way to generalize such a function to handle situations in which asymptotic accuracy was substantially below 100% correct performance. Thus, if one form of SAT function is to be general over conditions that differ in asymptotic accuracy, then it would seem necessarily to be a function with at least three parameters: intercept, rate (slope), and asymptote.

Instructions

One method of inducing subjects to respond at different speeds is to provide a variety of instructional sets that differentially emphasize speed or accuracy. This approach has been taken by a number of investigators including Hale (1969), Hick (1952), and Howell and Kreidler (1963, 1964). No one seems to have used the method to obtain an SAT function, but it could be so used. The method requires a subject to set some speed-accuracy criterion as a result of the instructions and maintain that over a block of trials to obtain a single point on the SAT function.

Payoffs

A considerably larger number of investigators have employed explicit payoffs for speed vs accuracy. Some of these studies have employed only a relatively small number of speed-accuracy conditions and plotted errors and reaction time separately for each condition, perhaps as a function of some other variable, such as memory set size, for example. Such studies include Banks and Atkinson (1974), Coots and Johnston (1972), Fitts (1966), Lively (1972), Lyons and Briggs (1971), and Swanson and Briggs (1969). Actual speed-accuracy tradeoff functions have been obtained using the pure payoff method by Swensson (1972), and Swensson and Edwards (1971). A variety of pure payoff methods might be used to generate an SAT function. The method used by Swensson (1972), was to pay a subject an amount, $[D - k \cdot (RT)]$, for a correct response and charge him $[-k \cdot (RT)]$ for an error. By varying the magnitudes of D and k in different blocks of trials, subjects were induced to respond at different speeds and make different percentages of correct responses.

Deadlines

Pachella et al. (1968) and Pachella and Fisher (1969, 1972), have used a pure deadline method for obtaining speed-accuracy tradeoff functions. This method involves instructing a subject to respond quicker than some time deadline, which might be 0.4 sec following the onset of the stimulus in one block of trials, 0.7 sec following the onset of the stimulus in another block of trials, etc. By providing feedback

regarding response times, subjects are able to learn to produce responses at a variety of different times, most of which fall below the deadline.

Other investigators such as Ollman (1966), Pachella and Pew (1968), Pew (1969), and Yellott (1971) have combined the deadline and the payoff methods using a 2×2 payoff matrix defined by correct vs incorrect responses and reaction times faster or slower than the deadline. By varying the character of this payoff matrix, subjects can be induced to respond at different speeds and with correspondingly different levels of accuracy. Once again, a particular deadline and a particular payoff matrix is typically employed for a block of trials over which speed and accuracy are assessed.

However, Link (1971) used a mixed deadline procedure involving three different deadlines with subjects instructed at the beginning of each trial regarding which deadline to respond prior to. Subjects were able to do this quite well and showed no sequential dependencies on the deadline employed in the preceding trial.

Time bands (time windows)

The deadline method imposes an upper limit on reaction times, but in some ways it would seem more desirable to impose both a lower and an upper limit on the reaction times in any speed-accuracy tradeoff condition. With this method, subjects are instructed or paid off to respond within some time band (time window) following stimulus onset. This method appears not to have been used thus far in generating speed-accuracy tradeoff functions, but Snodgrass et al. (1967) have shown that subjects can accurately time their responses to fall within such time bands, over a range that would be adequate for generating the speed-accuracy tradeoff function. One problem with both the deadline and time band methods is that the variance and possibly other characteristics of the reaction time distributions increase with increasing distance of the band or deadline from stimulus onset (e.g., Snodgrass et al. 1967).

Response signals

Schouten and Bekker (1967) manipulated reaction time in a way which is basically different from any of the previously described methods. Schouten and Bekker employed an auxiliary signal, actually a

series of signals, telling the subject when to respond following the presentation of the stimulus information to be judged. With the stimulus to be judged consisting of a visual signal, Schouten and Bekker employed a series of three auxiliary auditory signals (tone pips) each 20 msec long with intervals of 75 msec between them. Schouten and Bekker instructed subjects to make their decisions in coincidence with the third pip. Subjects were able to respond in coincidence with the third pip with a high degree of accuracy. By changing the onset time for this series of three pips in relation to the onset of the visual stimulus to be judged, Schouten and Bekker were able to achieve responses at a wide variety of different reaction times. Although it would not appear to be necessary, Schouten and Bekker presented each delay condition in a block of 100 trials.

By contrast, in a modification of the Schouten and Bekker method, Reed (1973, 1976) used the offset of the stimulus to be judged as the signal to respond and varied the time from stimulus onset to the response signal in a mixed manner. That is to say, all of the different delay conditions were mixed so that subjects did not know what delay condition they would be in on any given trial until the cue to respond occurred. There may be somewhat greater variance involved in a mixed, as opposed to a blocked, procedure. However, the mixed response-signal procedure would appear to be theoretically superior, since it guarantees that the subject is in the same state over the first t msec for any condition in which the cue to respond is greater than or equal to t . Under a blocked procedure, a subject may adopt different strategies for different blocks (different delay conditions).

Another feature of the Reed method that distinguishes it from the Schouten and Bekker method is that Reed used a *single* unexpected response signal, with subjects instructed to respond as quickly as possible following the presentation of the signal. By contrast, Schouten and Bekker deliberately employed a series of three pips at regularly spaced intervals, so that a subject would be warned regarding the time to respond shortly before the response was to be made. (Subjects coordinated responses to be more or less coincident with the third pip.) Both methods seem to achieve a satisfactory manipulation of mean response times following stimulus onset, and the variances of the reaction time distributions around those means appear to be not substantially different for the two methods. Only future research will tell which method is generally superior. Response to a series of three signals

with the requirements to respond in coincidence with the third signal would appear to be a more complex task than response to a single signal. If all other factors were equal, this would be a point in favor of the single-signal method, since the three-signal procedure presumably might have a greater negative effect on the primary information processing task. In fact, Schouten and Bekker (1967) concluded that their three-signal method did interfere somewhat with performance in the primary task. However, there has been so little work using these response signal methods that nothing definitive regarding this matter can be concluded at present.

Finally, it is fundamental to the speed-accuracy tradeoff method that one is attempting to look at the same SAT function at each different delay interval. This appears to lead to two conclusions. First, in the absence of any direct information that a blocked procedure does not induce different strategies for different delay conditions, it would seem superior to use a mixed procedure. Second, all of the methods for generating SAT functions, except response-signals, namely, instructions, payoffs, deadlines, and time bands are unsatisfactory, because they require that a subject be informed of the time condition prior to the presentation of information on a trial, even if these methods use a mixed rather than a blocked procedure. Only the response signal method, of all existing methods of manipulating response time, seems ideal from this viewpoint, since it does not require that a subject know the response time condition prior to about 200 msec before the response.

Partitioning reaction time

In all of the preceding methods, reaction time was largely manipulated by the experimenter through some means or another. By contrast, one can take a series of reaction times and partition them after the fact into those reactions between 200 and 220 msec, those between 220 and 240 msec, and those between 240 and 260 msec, etc., measuring accuracy within each partitioned reaction time band. This method takes advantage of the variability in response times. Schouten and Bekker (1967) used this method, which they called the method of 'free' reaction time, and contrasted it to their 'forced' method discussed previously. In the hands of Schouten and Bekker, the method of partitioning reaction times was not so satisfactory as the response signal

method, since subjects produced an inadequate number of responses at short reaction times. Thus, the initial very inaccurate section of the speed-accuracy tradeoff function simply could not be obtained by this method. Rabbitt and Vyas (1970) used a task in which subjects were more successful in obtaining a broad distribution of reaction times including many that were fast enough to achieve chance responding. The most systematic use of this method has been by Lappin and his associates (Lappin and Disch 1972a, b, 1973; Harm and Lappin 1973), where subjects have been instructed to respond at a rate that will produce approximately 25% errors. This high target error rate appears to produce a satisfactorily large variety of reaction times sufficient to sweep out the entire speed-accuracy tradeoff function in the very easy perceptual choice task employed by Lappin.

Partitioning vs manipulation of reaction time

Wickelgren (1975) has criticized the method of partitioning reaction times as a method of generating SAT functions as follows. To the extent that the SAT function is considered to be an average over randomly varying conditions of attention, arousal, etc., and to the extent that when the 'true' SAT function is higher for a given trial, responses are made more rapidly, the method of partitioning reaction times will tend to overestimate accuracy near the intercept and underestimate accuracy near the asymptote. Wickelgren cited the comparison of the two methods in the Schouten and Bekker (1967) study in support of this criticism. However, the response signal method in Schouten and Bekker was sufficiently complex that the difference may be due to underestimation of the accuracy of the 'true' SAT function at short delays using the 'forced' method, rather than overestimation of the accuracy by the 'free' (partitioned) reaction time method.

Taking a different, but related theoretical tack, Pachella (1974) goes so far as to claim that the SAT function generated by manipulating reaction times (which he calls the 'macro-tradeoff') is completely independent of the SAT function generated by partitioning reaction times (which he calls the 'micro-tradeoff'). Pachella's argument is that several different theories of the SAT function make similar predictions about the general form of the macro-tradeoff but completely different predictions concerning the micro-tradeoff.

Certainly, it is not known what the relationship is between SAT functions generated by the method of partitioned reaction times and SAT functions generated by manipulating reaction times. However, there is at least one possible hypothesis regarding the speed-accuracy criterion in which the method of partitioned reaction times would yield an unbiased measure of the true speed-accuracy tradeoff function. According to this hypothesis, the decision for a subject to respond is determined totally by setting a response time criterion, independent of the level of accuracy or discriminability thus far obtained. If all variability in reaction time is due to variability in this time criterion, which is independent of (uncorrelated with) the accuracy level (and therefore independent of fluctuations of attention, arousal, etc.), then the method of partitioned reaction times yields an ideal estimate of the true speed-accuracy tradeoff function.

It may prove to be the case, as Pachella suggests, that the method of partitioned reaction times is satisfactory only for investigation of extremely fast processes, that is to say, processes for which substantial speed-accuracy tradeoff obtains only over a period of about 150 msec, as in most of the studies by Lappin and his associates. For more difficult perceptual discriminations, memory retrieval tasks, or other more complex cognitive tasks, it will probably be necessary to manipulate reaction times in order to obtain the entire speed-accuracy tradeoff function in an efficient way.

Within a particular manipulated reaction-time condition, it may be useful to partition reaction times and plot the accuracy separately for two, three or four subdivisions of the distribution of responses generated within that condition. Incidentally, this application of the partitioning method is the origin for the use of the term 'micro-tradeoff', by Pachella, since it refers to a presumed smaller scale variation in accuracy within a very limited range of response times.

Using any method of manipulated reaction times and plotting accuracy as a function of mean actual reaction time is subject to a degree of bias which is greater, the greater the variance in the reaction time distributions. The nature of this bias, surprisingly enough, is also to overestimate accuracy near the intercept and underestimate it near the asymptote. The nature of this estimation error can be most quickly illustrated by an example. Imagine that one has obtained a manipulated reaction time whose mean (or other measure of central tendency) is centered on the 200 msec delay in fig. 1. At this point, the true

theoretical SAT function has an accuracy level at chance. However, since what has been generated is a distribution of response times centered on the 200 msec interval, some proportion of the slower reaction times will be 'looking at' a level of accuracy greater than chance, while those faster than the mean will be looking at chance accuracy. When the accuracies of these different reaction times are pooled, they will result in above-chance accuracy, particularly under the assumption that what causes variability in reaction time is variation in a pure speed (time) criterion. To the extent that what causes variation in the response time is derived from variation purely on an accuracy criterion, one might see no such distorting effect due to pooling.

This issue can only be resolved by looking at the micro-tradeoff function within a particular manipulated speed-accuracy tradeoff condition to see whether it is flat, as predicted by a pure accuracy criterion uncorrelated with fluctuations in the SAT function, monotonically increasing, as predicted by a pure time criterion uncorrelated with fluctuations in the SAT function, or monotonically decreasing, as predicted by a pure accuracy criterion strongly correlated with fluctuations in the SAT function. The uncorrelated time-criterion model makes the further strong prediction that the accuracy level obtained in a 200–220 msec band will be identical regardless of whether it was obtained from a reaction time distribution whose mean was centered at 190 msec or whose mean was centered at 230 msec. The classic study of Schouten and Bekker (1967) actually employed such a combination of partitioned reaction times within manipulated reaction-time distributions, that is to say, Schouten and Bekker actually looked at both macro- and micro-tradeoff functions (see their figures 2 and 3). Although the results are far from definitive, the comparison of micro- and macro-tradeoff functions in Schouten and Bekker is fairly consistent with an uncorrelated time criterion theory of the variability in reaction-times. That is to say, it appears that responses within a particular time band have the same accuracy level regardless of whether they were particularly fast reactions from a distribution whose mean was greater than that time band, or particularly slow reactions from a distribution whose mean was less than the band. Whenever this result is obtained, the partitioning method is an unbiased way to obtain an SAT function. However, in recognition memory experiments, we have obtained monotonically decreasing micro-tradeoff functions consistent

with an accuracy criterion correlated with fluctuations in the SAT function. Pachella (1974) may well be correct, on several grounds, in concluding that the partitioning method will prove useful primarily in situations where the SAT function reaches asymptote quickly (150–250 msec), as it does in simple perceptual choice tasks.

Curve fitting and parameter estimation

If the micro-tradeoff function does not coincide with the macro-tradeoff function or one does not have a sufficient number of reaction times within a particular manipulated reaction-time distribution to justify partitioning into three or more classes, there is an alternative analytical procedure for avoiding the biasing effect of pooling over reaction times at different accuracy levels. This method is employed at the time one estimates the parameters to obtain the best-fitting theoretical speed-accuracy tradeoff function to fit a particular set of data. If one is using some hill-climbing method of parameter estimation and goodness-of-fit testing, one assesses the goodness of fit of a particular theoretical SAT function by multiplying the empirical probability density function for any reaction time distribution by the theoretical speed-accuracy tradeoff function to obtain an estimate of the empirical accuracy level for that distribution of reaction times. This estimated accuracy will lie above the true level of accuracy for times near the intercept of the SAT function and slightly below the true SAT function for some points close to the asymptote (but not points well out on the asymptote).

Theories of speed-accuracy tradeoff

At present, there appear to be three basic classes of speed-accuracy tradeoff theories: fast guess theory, the discrete process theory with a distribution of finishing times, and the continuous strength-integration theory. According to the fast guess theory (Ollman 1966; Yellott 1971), a subject can emit either a random guess with short latency or a stimulus-controlled response at considerably longer latency. Under speed conditions, a subject increases the proportion of fast random guesses to stimulus-controlled responses. Although use of the payoff

method seems to have induced subjects to use this fast guess strategy on some occasions, it is now perfectly clear that speed-accuracy tradeoff functions, in general, are not the result of different proportions of fast guesses (Pachella 1974; Reed 1973; Swensson 1972). Additional evidence against the fast guess theory comes from applying the logic of Pachella (1974) to the micro-tradeoff functions obtained by Schouten and Bekker (1967) which are exactly opposite to that predicted by the fast guess theory.

Superficially, the relatively continuous increase in the speed-accuracy tradeoff function with increasing processing time might suggest that the judged attribute is continuously increasing in strength. However, such continuous, monotonically-increasing functions can, of course, be generated from a discrete (all-or-none) process with a distribution of finishing times that extends over the dynamic range of the SAT function. At present, I know of no results that would distinguish which of these two very general classes of theories is correct. In analogous situations in perception and memory, it has proven extremely difficult to distinguish between discrete and continuous theories by any simple set of experimental observations. Over a long period of time, it may turn out that theories formulated within either the discrete or continuous framework will prove to be more parsimonious in accounting for all the data. Based on past experience, it seems doubtful that we can definitely decide between these two broad classes of theories in the near future.

Why speed-accuracy tradeoff experiments are superior to reaction-time experiments

Because subjects have the capability to tradeoff accuracy for speed, we cannot compare the reaction times obtained in two different conditions and conclude that the condition with the slower reaction time was 'harder' than the condition with the faster reaction time, unless we know that the error level in the slower condition was greater than the error level in the faster condition. When both errors and reaction times go in the 'same' direction, then it is reasonably safe to conclude that the condition which is slower and has more errors is more difficult than the condition that is faster and has fewer errors. However, even here, there is some danger, since mean reaction time for a condition is often

estimated with sample sizes that are too small to obtain very accurate estimates of error percentage. Whenever this is the case, the possibility that the error percentages are in the 'same' direction as the reaction time differences due to a statistical sampling error may be quite substantial. Since the significance levels associated with the reaction time difference do not take this additional source of error into account, a difference in reaction time which is significant of the 5% level might actually be insignificant if the variability of the accuracy level were taken into account. However, this is a reasonably unlikely circumstance, and, in general, it is safe to conclude that the condition which is slower with more errors is more difficult than the condition which is faster with fewer errors.

Obviously, in a properly reported reaction time experiment, one must include a statement of the error percentages for *each* condition in the experiment. It will not do to state what the overall error percentage was, averaged across all conditions. Nor will it do to state the error percentage was low. In fact, as Pachella (1974) and Wickelgren (1975) have emphasized, it is precisely at low error rates where the variation in reaction times is enormous for extremely small differences in error percentage. Thus, the basic logic of most reaction time experiments is in error. It is *not* desirable to obtain reaction time measurements at low error rates (high accuracy levels), precisely because the form of the tradeoff function (as shown in fig. 1 or see Reed 1973, 1976) is such that at high levels of accuracy, tiny changes in accuracy can result in tens or hundreds of msec of difference in reaction time. Since this variability is enormous compared to most reaction time differences, it is clear what a significant factor speed-accuracy tradeoff can be at low error rates.

Even if an experiment carefully measures and reports the error rates, it is somewhat risky to run a standard reaction time experiment in order to investigate whether one condition is more or less difficult than another condition, since one cannot be sure that one will obtain errors in the 'same' direction as reaction time. However, it does appear that reaction times and errors usually do go in the 'same' direction, so the risk is far less than 50-50. Furthermore, speed-accuracy experiments require from five to ten times as many trials as reaction time experiments. Hence, it is completely reasonable to do a conventional reaction time experiment to determine simply whether one condition is harder than another condition, provided errors are measured and reported for each condition.

What may not be defensible, at present, is to attempt to test quantitative theories of information processing dynamics, such as the memory scanning theory of Sternberg (1966, 1967, 1969), by functions which use reaction time as the sole dependent variable, without simultaneously predicting accuracy. Because of the basic fact of speed-accuracy tradeoff, we know that any level of reaction time might be obtained in any condition depending upon what level of accuracy the subject decided to adopt in that condition. Because of this, it seems relatively meaningless for a theory to predict reaction times unless it predicts accuracy levels as well. Along the same line, the linearity of such reaction time functions and their parameters (slopes and intercepts) may be meaningless, since the form of the function and its parameters can be completely changed by a change in the subject's speed-accuracy criteria. There is now considerable support for this theoretically certain conclusion in the empirical literature. Pachella (1974) and Wickelgren (1975) have discussed this point at great length.

To be completely fair, we do not know for certain that subjects' capability to achieve any degree of speed-accuracy tradeoff (from chance to asymptotic accuracy) under speed-accuracy tradeoff instructions implies that this capacity is used under reaction time instructions. Perhaps in reaction time experiments, all subjects use the same speed-accuracy criterion and use it under all conditions. If this were the case, it might be reasonable merely to predict reaction time functions, ignoring error rates (though it would seem that ultimately a complete theory should also be able to predict error rates). The reader will just have to judge how likely it is that subjects have some invariant speed-accuracy criterion across all conditions and all subjects. Certainly different conditions and different subjects exhibit vastly different error rates. Thus, any hypothetically invariant speed-accuracy criterion is not a simple invariant accuracy criterion (nor, of course, could it be an invariant speed criterion). In the absence of any information supporting the assumption of an invariant criterion in reaction time tasks, it seems scientifically cautious to assume that the demonstrated *capability* of subjects to vary their speed-accuracy criterion may translate into the *fact* of such variation in ordinary reaction time studies. If speed-accuracy research validates some of the quantitative models currently grounded on reaction time data, so be it. The point is that we need speed-accuracy tradeoff data to be sure that uncontrolled variations in criteria are not producing misleading data in reaction time tasks.

Although the basic fact of speed-accuracy tradeoff may make it inadequate to look at reaction time alone as the dependent variable, it does not invalidate looking at asymptotic accuracy as a dependent variable without reference to reaction time. The fact that speed-accuracy tradeoff functions approach an asymptotic level of accuracy at long reaction times means that so long as the response time is sufficiently long to ensure that one is operating at or near the asymptote, enormous differences in response time will be associated with negligible differences in asymptotic accuracy. Thus, there is little opportunity for contamination of asymptotic accuracy by differences in response time, while there is considerable opportunity for contamination of reaction time by differences in the level of accuracy. Studies that examine only asymptotic accuracy are essentially not concerned with the same questions as are studies that examine reaction times. Reaction time studies are generally concerned with the dynamics of perceptual, memory, or cognitive decision making processes. That is to say, people have looked at reaction time when the emphasis has been on determining the number of stages and the nature of processing that goes on within the first few hundreds of msec following the presentation of a stimulus. To study this type of dynamics, one must look at *both* speed and accuracy.

One might agree with the points made in the preceding paragraphs without believing that speed-accuracy tradeoff functions were the way to go in the future. An alternative approach is to predict accuracy as a function of various conditions and simultaneously predict reaction time as a function of these conditions, rather than predicting the speed-accuracy tradeoff function. There is no way to know at present which approach is superior. However, the speed-accuracy tradeoff functions that have been obtained so far appear to have very elegant properties. In a few cases, it has been determined that subjects who differ in accuracies and reaction time distributions have virtually identical speed-accuracy tradeoff functions (Schouten and Bekker 1967). Lappin and Disch (1972a) have shown that differences in stimulus probability that affect accuracy and latency, nevertheless produce the same speed-accuracy tradeoff function. To the extent that the speed-accuracy tradeoff functions are more invariant over a variety of conditions than either speed or accuracy functions alone, there is a strong argument in favor of the speed-accuracy tradeoff function.

Another argument in favor of SAT functions, are the three intrin-

sically interesting parameters of such functions, namely, intercept, rate, and asymptote. If some independent variables produce effects on the intercept, but not on the rate and asymptote, while others produce effects on only the asymptote but not on the rate and intercept, etc., then that would be another argument in favor of SAT functions. Of course, with so many options available at present regarding the choice of the accuracy and time measures, it will be some time before we can determine which type of speed-accuracy tradeoff function works best and indeed whether any such function will prove to be superior to a separate prediction of speed and accuracy. However, the prospects are very promising at present.

There is a final point of great importance. Whether you plot SAT functions or separate reaction time and accuracy functions, there is a strong *empirical* argument in favor of performing *speed-accuracy tradeoff experiments* as opposed to reaction time experiments. The argument is as follows: The principal reason for doing reaction time experiments is to describe (and test theories of) information processing dynamics during the first several hundred msec following stimulus presentation. The other common reason for studying reaction time has been to supplement the accuracy measure in cases where accuracy is essentially perfect and a more sensitive indicator of differences in response strength is needed. Some of the preceding arguments against conventional reaction time apply to this use, but the following empirical argument is inapplicable.

In those cases where the focus is on testing theories regarding information processing dynamics, speed-accuracy tradeoff experiments are far superior to reaction time experiments. Studies of information processing dynamics are concerned with questions such as the number of processes that take place in reacting to a stimulus, the rates at which these processes occur, whether the processes are performed sequentially or simultaneously, etc. A reaction time experiment attempts to answer such questions by means of a single reaction time and its associated accuracy per condition, at a point generally quite far out on the asymptote of the speed-accuracy tradeoff function. That is to say, the conventional reaction time experiment obtains a single measurement of speed and accuracy to describe the entire process and obtains that single measurement at a point when virtually all of the processing is over. By contrast, a speed-accuracy tradeoff experiment obtains measurements of speed and accuracy at a large number of points

following stimulus presentation. Furthermore, these measurements are taken during those initial hundreds of msec in which the processing is taking place. The increased power of such a method for deciding between different theories of information processing dynamics should be obvious. One is taking measurements 'where the action is'. 'Interpolation is superior to extrapolation'. However you say it, much more information can be obtained from the entire speed-accuracy tradeoff function and also from the relationship between response latency and manipulated lag condition (what Reed 1976 calls the lag-latency function). To be sure, a speed-accuracy tradeoff experiment requires the collection of at least five times as much data as a standard reaction time experiment, so experiments designed only to determine whether one condition is harder than another should usually employ a reaction time design. However, the prospects of achieving cumulative scientific progress in quantitative studies of cognitive dynamics seems so much greater when one obtains the entire SAT function that such data should often be well worth the extra time and expense.

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