Research Article

SERIAL VS. PARALLEL PROCESSING: Sometimes They Look Like Tweedledum and Tweedledee but They Can (and Should) be Distinguished

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Abstract—*A number of important models of information processing depend on whether processing is serial or parallel. However, many of the studies purporting to settle the case use weak experimental paradigms or results to draw conclusions. A brief history of the issue is given along with examples from the literature. Then a number of promising methods are presented from a variety of sources with some discussion of their potential. A brief discussion of the topic with regard to overall issues of model testing and applications concludes the paper.*

Somewhat informally, serial processing means strictly sequential, without overlap of the successive processing times on objects or distinct subsystems. In a standard type of serial system, each object takes the same average amount of time to process and the next object begins processing only when the previous one is completed. On the other hand, parallel processing signifies simultaneous processing on several objects or subsystems at the same time, although processing may finish on different objects at different times. In either type of operation, both individual and overall processing times may be random. That is, the durations required for processing an item or performing an operation may vary from trial to trial. This paper is about testing parallelism vs. seriality.

The question as to whether and when people can perform perceptual or mental operations in parallel began to receive experimental treatment in the late 19th century, although not under these names. It was a natural question for the emerging discipline of psychology because it is inherently related to the capacity of mind and how that capacity is allocated to sundry cognitive and perceptual endeavors. Perhaps Hamilton (1859) was the first to attempt an empirical, if hardly experimental, answer to the question. One of his techniques was to toss several dice on his desk and try to assess "instantaneously" the number of dots showing. The intent was to determine the number of objects that could be apprehended simultaneously (i.e., in parallel) by human consciousness. This interest reappeared in various guises in the emerging psychological laboratories of the world. It remains a lively research topic today in diverse areas of pure and applied cognitive psychology. The longevity of the topic is probably due to its fundamental importance in describing how mental operations take place.

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As intimated above, this topic is also closely connected with the issue of capacity; that is, to what extent mental processing of some type suffers when the number of things to do mentally or the difficulty of the cognitive operations increases. For instance, standard serial processing with each successive subtask taking the same average duration is of limited capacity with respect to the overall total processing time required for an increasing number of subtasks. That is, the overall reaction time for all the subtasks increases, the more tasks there are to do. However, the same serial processing is of unlimited capacity on individual items in the sense that the average item processing duration per item is constant regardless of the total number of items to be done. Parallel processing can be either limited or unlimited capacity on either the individual item or on the whole set, the difference depending on the type of parallel system in question (e.g., Townsend, 1974a, Townsend & Ashby, 1983).[1]

This paper will advocate the view that contemporary research on the parallel-serial question often uses methodology or logic that was shown to be faulty or at least precarious twenty or more years ago. Also, it is argued that few investigations take advantage of more powerful techniques of testing the dichotomy that have been developed since 1968. Several pertinent examples will be given from the literature in perception and cognition. In the following section, a number of promising methods that can be mathematically demonstrated to separate large classes of parallel vs. serial models will be collated from the literature and explained.

HISTORICAL PERSPECTIVE

A very brief, limited survey of the recent history of the issue

1. We are presently concerned strictly with models that may be referred to as traditional serial or parallel models. Introductions to certain other types of models may be found in Meyer, Irwin, Osman & Kounios (1988) and Ratcliff (1988) along with many references. More technical information on the traditional and some of the more recent models can be found in Luce (1986) and Townsend & Ashby (1983).

may help place the situation in perspective. It seems likely that the late 20th century revival of the serial vs. parallel issues was connected with the "bottleneck" conception of human information processing (e.g., Broadbent, 1958; Treisman, 1969). Theoretical emphasis on seriality of item processing in both perception and short-term memory search increased during the early 1960s with the establishment of the information processing paradigm and, in particular, with the investigations of Sperling (1960, 1963), Estes and Taylor (1964, 1966), and the later treatise by Neisser (1967).

In a crucial paper, Sternberg (1966) persuasively interpreted short-term memory search reaction time data in terms of serial search and disconfirmed a significant class of parallel models.[2] The crux of Sternberg's demonstration was a strikingly linear function relating reaction time to the number of items to be searched. His work was instrumental in firmly wedding the concept of increasing straight line set size functions, to seriality of processing in the minds of cognitive scientists. In contradistinction, parallel processing has, then and now, often been supposed to imply that reaction time remains constant as the mental load is increased.

Many writers still implicitly assume that parallelism does imply constancy of both reaction times and accuracy, as more contemporary references below will show. However, as recognized by Egeth (1966) in an early study of serial vs. parallel processing of featural dimensions, even unlimited capacity parallel processors can yield increasing mean reaction time function in a natural way. By "unlimited capacity" here, is meant that the average time to process a single item does not vary with the total number of items undergoing simultaneous (parallel) processing. If the individual processing times vary from trial to trial, as we expect with humans, such unlimited capacity parallel models typically predict that the mean overall completion time on a set of items will increase as a function of the set size (see Egeth, 1966; Townsend, 1974a, or Townsend & Ashby, 1983).

An important aspect of such parallel processing is that all mean set size functions associated with this type of processing are predicted to be negatively accelerated (Townsend & Ashby, 1983, pp. 92-93). Sternberg (1966) took the disparity between the fastest increasing parallel predictions and his observed linear functions to rule out parallel processing. However, it was apparently not widely appreciated at the time that this demonstration did not rule out the vast class of limited capacity parallel models.

Soon thereafter, however, a number of authors began to notice the potential of limited capacity parallel processes to mimic the straight line predictions of standard serial models. Some of these models seemed unrealistic in that each subtask was processed deterministically, with zero time variance (e.g., Corcoran, 1971). Murdock (1971) proposed a parallel model for search experiments. Atkinson, Holmgren and Juola (1969) offered a more natural nondeterministic model that mimicked serial processing and the present author showed that each type of model could mimic the set size function of the other (Townsend, 1971a, 1972). Townsend (1976) and Vorberg (1977) developed theorems exhibiting equivalence among wide classes of parallel and serial models.

Following the early 1970s there was a hiatus in empirical tests of parallel vs. serial processing, possibly due, to some extent, to the ability of parallel and serial models to mimic one another in the common experimental paradigms.

Nevertheless, the issue has refused to fade away. The case may be put forth that how subtasks are worked on is an integral description of any real-time model and that other interesting questions also hinge on the temporal nature of the processing. Townsend and Ashby (1983) reviewed the parallel-serial controversy and presented a number of fundamental ways in which serial and parallel processing differ. The phenomenon of linear increasing reaction time curves is no longer considered a fundamental parallel-serial distinction because it simply indicates first and foremost, a limitation in capacity. That limitation may be due to seriality, limited capacity parallel, or even hybrid processing mechanisms. On the other hand, under certain conditions flat reaction time curves and sometimes even negatively accelerated curves can be strong indicants that processing is parallel (Egeth, Jonides & Wall, 1972; Townsend & Ashby, 1983, pp. 76-98). This state of affairs leads to an asymmetry in strength of inference that has been accorded insufficient attention in the literature.

The empirical side of the parallel-serial issue never entirely disappeared and, over the past few years, studies purporting to bear on it have again burgeoned. Unfortunately, their theoretical underpinnings have often been less than desirable. There seems to have been something of a regression to the reflex response, "linear increasing reaction time functions imply serial processing."

Some of the more frequent defenses of this strategy are to take brief note of the dilemma and then: (a) Claim parsimony or plausibility as did Schneider and Shiffrin (1977), Treisman (1982), and Treisman, Sykes and Gelade (1977); (b) Argue that they have acquired much data and provided a comprehensive theory, which nullifies the hazard (e.g., Treisman & Gormican, 1988); or (c) Allude to the issue in a somewhat oblique fashion (e.g., ". . . a slow, possibly serial, item-by-item comparison . . .", Schneider & Shiffrin, 1977, p. 477). Parsimony is unfortunately difficult to measure and while a useful concept, is often found in the eye of the theorist and therefore should be employed with caution. Converging evidence and an overall theory are to be universally applauded as an approach. However, the parallel-serial dilemma has, in this author's opinion received inadequate resolution in several of the efforts at comprehensive theory, particularly considering the importance the issue bears for the data interpretations in many of the relevant studies. The oblique approach, while innocuous to experts, may seem perplexing to readers who are not already steeped in the parallel-serial debate.

2. In the interest of space and because of the popularity of the reaction time argument, we will concentrate on that dimension in offering a historical perspective. However, much of the rationale immediately pertains to the claim that certain types of accuracy curves in the context of load or degraded display paradigms imply serial processing (e.g., Sagi & Julesz, 1987; Sperling, 1963, 1967). Townsend (1981) showed how typical first order accuracy results in whole-report performance can be predicted by either serial or parallel models. Certain promising methods based on accuracy will appear later in the paper.

In following up on the parsimony response, it may be debatable as to whether the serial explanation is always the more parsimonious for increasing reaction time functions, particularly when unaccompanied by converging operations. Thus, when processing becomes closer to unlimited capacity parallel processing (e.g., Schneider & Shiffrin, 1977; Egeth, Jonides & Wall, 1972) through practice, for instance, it seems to this author more parsimonious that the shift be from a limited capacity parallel processor than from a serial mechanism. The former resides within the same qualitative type of system, unlike the latter. An opposing view and detailed model are put forth by Schneider and Detweiler (1987).

Aside from the specific criticisms mentioned above, what is wrong with a "serial by convention" strategy from a more global point of view? If we cannot tell the difference anyway, why shouldn't we simply call processing "serial"? One rebuttal is that if the issue is important enough to report on, or if it bears critical implications for the interpretation of one's data, then it is important enough to test in its own right. And the test should optimally offer some hope of discriminating broad classes of the opposing concepts. Linear set size functions do not perform that function, but newer techniques exist that do.

Another problem with the "convention" approach is that an uncontested convention tends to rather quickly evolve into an accepted fact. The "as if serial" becomes "the serial." This approach also may encourage succeeding generations of researchers to continue to beg the question or confuse the issue with the capacity limits problem.

There are now, as noted above, experimental strategies based on mathematical demonstrations available to help determine whether processing is serial or parallel. Why not employ them? The following text outlines some of the promising techniques for testing parallelism vs. seriality. They are brought together from a number of sources, some of them perhaps not readily accessible and some of them stated in rather technical language and mathematics. The latter may be one reason for the apparent lag in assimilation of theoretical results.

Obviously, the details are beyond the scope of the present discussion. The main object here is to aid the reader in identifying the tests that seem especially promising and to provide some intuition about their rationale. Certain methods and parallel-serial distinctions that may lead to viable methods in the future had to be omitted. Townsend and Ashby (1983) provide a more complete account, but not all extant methods are covered there.

In closing this section, it should be remarked that although the above discussion has been devoted primarily to brief visual display and short-term memory search, the parallel-serial issue arises in many contexts. Indeed, it is sometimes present in different guises.[3] In construction of almost any cognitive system that depends on the real-time functioning of more than a single subsystem, the question must be faced of whether the subsystems or subprocesses are carried out in parallel, serially or in some hybrid fashion.

METHODS OF TESTING SERIAL VS. PARALLEL PROCESSING

First it should be acknowledged that as in all theory and measurement in science, assumptions must be made; in other words, there is no free lunch. Moreover, the degree and type of restrictions on the class of models covered by a paradigm will usually differ from those of other paradigms. That is a good reason, along with the fact that no method is perfect, to use more than one method to provide converging evidence. Most of the known methods are based on reaction time but some are based on accuracy. Undoubtedly, strong methods can be derived that involve reaction time and accuracy conjointly. And, the fact that a method has been most employed or studied theoretically with reaction time does not rule out its viability in the context of accuracy or vice versa. Finally, certain methods may ultimately prove to be more appropriate for certain cognitive situations or stimulus materials than others.

Methods Based on Reaction Time

The following list of methods is not exhaustive, due to space requirements but includes several of the most promising techniques.[4]

I. The Method of Factorial Interactions with Selective Influence of Cognitive Subprocesses

This technique is based on a postulate of selective influence by two or more experimental factors (see Ashby & Townsend, 1980; Sternberg, 1969). That is, it is assumed that experimental factors can be found that affect separate subprocesses (stages, subsystems, etc.). The investigator measures the mean reaction

3. One example is the debate, historical in human psychology (e.g., Hamilton, 1859; Hunter & Siegler, 1940; Kaufman, Lord, Reese, & Volkman, 1949) and ongoing both in human and animal psychology (in the latter case, see e.g., Capaldi & Miller, 1988; Davis & Pérusse, 1988) concerning to what extent a quantity of things can be "subitized" vs. "counted." The "counting" mechanism seems to bear implications for what a formalized account might call seriality (see, e.g., Klahr & Wallace, 1973; Mandler & Shebo, 1982) similarly, the "subitizing" mechanism clearly has overtones (sometimes explicit, sometimes not) of parallelism (e.g., see Atkinson, Campbell, & Francis, 1976; Mandler & Shebo, 1982; Sagi & Julesz, 1985a, b). Another area of research which overlaps the parallel-serial issue is that of "automatic processing" (e.g., Logan, 1978, 1985; Schneider & Shiffrin, 1977). Although the notions are far from identical, one way of implementing automaticity is through conversion to an unlimited capacity type of parallel processing (e.g., Schneider & Detweiler, 1987).

4. A nonparametric method developed by Thomas (1969a, b) and a test constructed by Ross and Anderson (1981), based on a parallel-serial distinction discovered by the author (Townsend, 1976), had to be omitted from the present review. They may be somewhat more difficult to implement and the background required for their comprehension is more technical than the methods covered here. Nevertheless, they may prove important in future experimentation. We also omit methods of increasing the load, such as the Sternberg memory scanning paradigm (Sternberg, 1966) because it was discussed above. Also as noted above, its primary strength arises when reaction time is flat rather than an increasing function of load.

time under all combinations of the various factor levels and then looks for interactions or the lack thereof, the latter to be clarified further below.

A historical precursor of factorial methods was the method of subtraction invented by Donders (1859). Donders assumed that a mental task could be formulated to include or exclude a particular cognitive subprocess. By measuring the reaction time under both conditions, an estimate could be gained of the average processing time consumed by the designated cognitive process. The method of subtraction is still useful despite its strong assumptions (e.g., Ashby & Townsend, 1980; Gottsdanker & Schrag, 1985).

In the method of factorial interactions, however, an experimental factor need not add or delete a subprocess, it need merely affect its processing time. A lack of interactions is referred to as *additivity* because the factors are affecting reaction time in a separately additive fashion. That is, the effect of Factor X, say, is the same whatever the level of another factor, Factor Y. Of course, it should be ascertained that both factors are having a definite effect before assessing the presence of interactions. That is, both factors should lead to significant main effects. It is typical to employ analysis of variance in such studies, to test for main effects and interactions.

The modern method of factorial interactions may be viewed as a descendent of Sternberg's (1969) additive factor method, just as Sternberg's method may be interpreted as a descendent of Donders' method of subtraction. Our method differs from Sternberg's in that we have proven that certain types of interactions imply distinct classes of mental architectures.[5] The original method postulated that the subprocesses acted in a serial fashion and concluded distinct subprocesses if the factors showed additive effects. If the effect was interactive, then those factors were taken as affecting the same subprocess. Thus, this method could be employed only to confirm seriality together with selective influence. Many studies found factorial additivity, although the statistical power in some of those is open to question (e.g., Pachella, 1974; Pieters, 1983; Theios, 1973; Townsend, 1984; these studies also provide general caveats with regard to factorial methods).

The two major types of interactions are subadditivity and superadditivity (e.g., Townsend, 1984). Subadditivity occurs when the amount of prolongation caused by a given factorial manipulation, say of Factor X, is less when Factor Y has already prolonged the reaction time. This is a negative type of interaction. Superadditivity is just the opposite, a positive type of interaction. That is, the increase in reaction time caused by Factor X is larger under the condition where Factor Y has already prolonged processing time.

Within our approach, it has been demonstrated that all independent parallel processes predict subadditivity when processing is exhaustive, that is when all subprocesses must be completed before a response can take place (Townsend, 1974b; Townsend & Ashby, 1983, see especially pp. 373-375).[6] Schweickert (1978) showed under more general conditions that factors prolonging concurrent processes in stochastic PERT networks would not be superadditive. We have also further delineated exactly when serial models can be expected to predict additivity (Townsend, 1984). This work has been generalized to non-independent parallel and serial models (Schweickert & Townsend, 1989; Townsend & Schweickert, 1985). Similar methods apply to much more complex mental architectures (Schweickert, 1978; Schweickert & Townsend, 1989; Townsend & Schweickert, 1985; Townsend & Schweickert, 1989). Finally, it can be shown by similar techniques that if the first subprocess to be finished initiates the next stage, then superadditivity is predicted by independent parallel processes (Townsend & Nozawa, 1988).

II. The Parallel-Serial Tester

Snodgrass (1972) instituted a pattern matching paradigm that gave promise of being able to separate certain classes of parallel and serial models. Townsend (1976) later developed a theory of stochastic matching processes which delineated a number of fundamental distinctions between parallel and serial operations. Several of these were put together in such a way as to produce the parallel-serial tester (PST), which can be viewed as a simplification of Snodgrass' original design, and which was shown mathematically to distinguish all parallel vs. serial models based on an important class of probability distributions.

Basically, the method consists of three experimental conditions. Each condition involves the perception of two patterns (words, pictures, categories, etc.), which we refer to as A and B. In condition CI, the subject must determine which of two positions is occupied by pattern A. Response R1 is made if it is in one of the positions and R2 is made if A is in the other position. There are two types of trials, AB and BA. Condition CII requires four trial types, AA, AB, BA, and BB. The subject responds R1 only if both patterns are A and R2 otherwise. This is a conjunction mode of processing. The final condition, CIII, also uses the four pattern types of trials as in CII, but now the response mode is disjunctive. That is, the subject responds R1 if any of the patterns is A and otherwise responds R2. Thus, in the latter case, R2 occurs only when the stimulus BB is presented. Note that these conditions can be blocked separately or, with appropriate cues on each trial, intermixed within blocks.

The theory assumes that processing is self-terminating; that is the subject can cease processing when enough information has been gained that a correct response can be made. It is also assumed that errors are few and do not covary in an important way with reaction time. It is subject to the possible criticism that subjects may not process in the same (parallel or serial) mode in the three conditions.

PST has been generalized to be distribution free (see Townsend & Ashby, 1983, Chapter 13 for the exact mathemat-

5. Taylor (1976) promotes the use of linear interactions to draw conclusions about the spatiotemporal nature of processing. It can be shown that ordinary parallel processes do not obey the precepts required for temporal overlap in his scheme, but it may prove useful in studying so-called "contingent serial processes" (cf., Miller, 1988).

6. Alternatively subadditivity could be associated with a Wheatstone Bridge (Schweickert & Townsend, 1989). Although theoretically possible, this seems less probable than parallelism in the present circumstances.

ical specification). It has received some experimental probing in its more general (Snodgrass & Townsend, 1980) and in its more specific form (Townsend & Snodgrass, 1974). Within this limited experimental arena, the results appear to depend on the complexity of the matching required of the subject. With more complex patterns and processing requirements, subjects appear to be forced to resort to serial processing (e.g., Snodgrass, 1972; Snodgrass & Townsend, 1980), whereas in the simpler versions of the paradigm and with elementary patterns, there is a suggestion that subjects can operate in parallel (Townsend & Snodgrass, 1974). PST also seems to be a promising candidate for extension to accuracy based experiments.

III. The Method of Redundant Targets

In this visual display search method, one type of trial contains no targets among the *n* items, and demands one kind of response, for instance a "no" response. The other type of trial presents one or more targets and requires the other type of response, for example a "yes" response (Egeth, Folk & Mullin, 1988; Wolford, Wessel & Estes, 1968). It is postulated that processing is self-terminating, that is, processing can be terminated as soon as the first target is located. But the nature of the design permits assessment of this postulate. There are two major classes of this paradigm. The first form keeps the perceptual set size constant and varies the number of targets among the distractors (e.g., Wolford, Wessel & Estes, 1968). This form does not generally discriminate parallel from serial processing but can be used to test self-termination versus exhaustive processing and certain other issues. The second form or class of this paradigm includes a mixture of all-target and all-nontarget displays with the number of items in the display varied. Thus, the number of targets varies perfectly with display size here. As the number of targets increases, all unlimited capacity and many limited capacity parallel models predict that reaction time will decrease (e.g., Snodgrass & Townsend, 1980, pp. 335-337). Contrarily, serial models predict that reaction time will be constant across the number of targets present, because the average time to process a single target item (remember that only one, namely the very first one on such trials has to be completed) should not change with the total number of targets (e.g., Townsend & Ashby, 1983, pp. 80-92). A study by van der Heijden (1975) contains both forms of the paradigm and concludes that the combined data support a limited capacity, self-terminating, parallel model. Caveats about application of the method are offered by Snodgrass and Townsend (1980), van der Heijden, La Heij and Boer (1983) and Egeth, Folk, and Mullin (1988).

There have been a number of applications of this strategy. Overall, it seems fair to say that parallel processing is most supported (see, e.g., the study and discussion by Egeth, Folk and Mullin, 1988). If the redundancy leads to very substantial gains in speed, then even ordinary parallel models may not be able to handle the data (e.g., Miller, 1982). Miller (1982, 1986) and Colonius (1986) discuss some probabilistic techniques for dealing with redundancy gains.[7]

Methods Based On Accuracy

IV. Tests by Time Delimitation

Suppose a subject has *n* items, say 5, to be processed in some variety of cognitive task. Consider the situation where in one condition, a duration *T*, say 200 msec is allotted to the subject for processing all 5 items. Here, if processing is serial, only approximately 40 msec can be consumed on each item. If the mechanism is parallel, all items receive 200 msec of processing. In the other condition, there are *n* successive time intervals of length *T*, each interval with exactly one of the items made available for processing. Thus, there will be a total of $5 \times 200 = 1000$ msec of exposure in the second condition, each item receiving 200 msec of presentation. If processing is serial, each item gets 200 msec of work on it rather than the 40 msec of the first condition. If parallelism holds, each item continues to receive 200 msec just as in the first condition. If accuracy is just as good in the first condition as the second, then parallel processing is supported because serial processing should rightly show a decrement due to a severe reduction in available processing time in the first condition. Conversely, if accuracy shows a large decrement, then seriality is (somewhat more weakly) supported. Eriksen and Spencer (1969) and Shiffrin and Gardner (1972) employed this technique and acquired support for parallel processing.

The author and his colleagues (Townsend, 1981; Townsend & Ashby, 1983, Chapter 11; Townsend & Fial, 1968) developed a natural counterpart to that paradigm, in which the first condition was identical to the above, with *T* time units duration available on all the items simultaneously. In the second condition, *n* successive time intervals, each of duration T/n are permitted for processing each item, and each item is allotted to a single interval. Adapting the above example, each item would be exposed for 40 msec in the second condition. If the serial model is the correct explanation, there would be 40 msec available under either condition so performance should be about equal in the two cases. However, if processing is parallel, each item acquires more time under the first condition, 200 msec as opposed to 40 msec. Therefore, acuracy is expected to decline from the first to the second condition under parallel processing. The experimental results were also in favor of parallel processing in the applications of this technique (e.g., Townsend, 1981). An implicit assumption in both strategies is that serial processing is not disturbed by the sequential presentations. Although these two methods appear to be quite powerful, a few models may be indiscriminable due to parallel-serial mimicking.

V. The Second Response Paradigm

In some respects, serial models are more general than parallel, especially within the province of reaction time modeling (e.g., Townsend, 1976; Townsend & Ashby, 1983). This means that it is impossible in some cases to gain definitive support both for the parallel model and against the serial, because the

7. There is a more or less separate literature of experiments where redundancy actually prolongs or has no effect on response times (e.g., Johnson, 1977, 1986; Krueger & Shapiro, 1980a, b). Johnson & Blum (1988) have made progress toward settling some issues in this domain. However, it still appears far from settled just how the latter relates to the type of study discussed here, where strong redundancy gains are typically found.

parallel models are contained within the serial class. It is critical to understand that this does not mean that a parallel machine of this type, made out of wires, gears or neurons, works in real time like a serial machine—only that the mathematical description of the parallel class of machines is contained within the mathematical description of the serial class *for a particular paradigm.*

Interestingly, in moving to the domain of accuracy experiments, the tables are turned in that the parallel class of models is often more general than the serial. This is because the processing state space (more technically, the probability sample space) for information accrual over time is more complex for the parallel models in general. In essence, parallel models as well as certain hybrid time sharing models (see Townsend & Ashby, 1983, pp. 61-65 and 470-471) can predict that if processing is stopped at an arbitrary point in time, any number of items may be in a state of partial processing. For instance, if the cognitive system is processing features in parallel on several items, then cessation of processing can leave each item with some features completed. In contrast, it is a hallmark of serial processing as the convention has been maintained over the past twenty years or so, that one item is completed at a time, with the succeeding item not being started until the last is finished (e.g., Townsend, 1974a). Therefore, if processing is sharply terminated, at most one item should be in a state of partial processing. This will not ordinarily show up in the overall accuracy results of a typical experiment. (But see the next section for a related technique where it can.)

In order to exploit this distinction, Townsend and Evans (1983) developed a technique based on a second response on each item to be processed. It was demonstrated that the pattern of accuracy on the second responses differed for serial vs. parallel models. Null hypotheses for serial processing within several levels of constraints on responding in the serial models were introduced and the results applied to a pilot experiment. Within the study, the data passed the tests for the most lenient serial hypothesis but ran into trouble with the more restrictive criteria. Currently, we are developing alternative parallel models for testing against the serial class and for examination of statistical power of the serial null hypothesis tests (Van Zandt & Townsend, in preparation). A potential vulnerability of this strategy is that in some applications, the second response might be based more on the first response than on the cognitive or perceptual processing associated with the first response. For this reason, it is helpful to pair this method with others such as the one following.

VI. A Similarity and Confusion Technique

A natural strategy within the context of accuracy experiments is to examine the pattern of confusions across items. Because parallel processes typically leave items in a partially processed state when processing duration is terminated by end of exposure, a response signal or the like, as discussed above in Method V, it is expected that the frequency of confusions among similar items should be greater than in the case of serial processing. That is, when processing is serial, there should be at most one item that can be confused with a similar alternative on each trial. Thus, there should never be more than one item confused with those most similar to itself except by chance.

There are several ways of exploiting the foregoing prediction. One is to remove a single confusion from each trial report and then use an appropriate model to estimate similarity and bias parameters (e.g., the similarity choice model, see Luce, 1963; Shepard, 1958; Townsend, 1971b; Townsend & Landon, 1982). If the similarity estimates are substantially larger for pairs of items that are "obviously" more similar, or deemed to be so in regular recognition experiments with similar stimuli, then support is garnered for parallel processing.

As in paradigm (Method V) just above, this method cannot discriminate parallel processes from hybrid processes which permit partial processing on the separate items at any point in time. Random time sharing models are of this variety (e.g., Townsend & Ashby, 1983, pp. 61-65) as are certain quasi-serial models which posit a sequential sweep across the items, where only partial information may be acquired from each item in the sweep (e.g., Eriksen & Murphy, 1987; Schulman, Remington, & McLean, 1979; Yantis, 1988).

This technique is being prepared for use along with the second response Method III (Van Zandt & Townsend, in preparation). The only data of which we are aware that immediately relate to this strategy come from a whole-report study by Wolford and Hollingsworth (1974). Although their interest was not in the parallel-serial issue per se, their confusion analyses may be supportive of parallel processing since they discovered substantial evidence for visual confusions. However, they did not correct for the possibility that one confusion could occur from serial processing on each trial.

DISCUSSION

It seems appropriate to give an example of how an investigator might go about applying the above strategies. Certain strategies are more natural in some contexts than others. What about the popular situations where the stimuli are made up of several items and on target trials one of the items is a target and on the remainder of the trials, no item is a target (Atkinson, Holmgren & Juola, 1969; Sternberg, 1966; Townsend & Roos, 1973; Treisman & Gormican, 1988)? The subject responds "yes" in the former case and "no" in the latter. Accuracy is typically high and the major dependent variable is reaction time. The major independent variable is set size, that is, number of items in the stimulus display. As noted earlier, if reaction time increases very much (this itself is usually a subjective aspect of the experiments) then processing is said to be serial, especially if the reaction times appear more or less linearly related to set size (again, tests of linearity are rarely performed). If reaction time curves are more or less flat, then processing is said to be parallel.

How can we be sure that processing is not simply limited capacity parallel in the former case? As Treisman and Gormican (1988) observe, converging evidence is required to support that claim. One immediate and natural supplementary technique might be the redundant targets paradigm (Reaction Time Method III), as employed by Egeth and his colleagues and others (see, e.g., Egeth, Folk & Mullin, 1988). If reaction time decreases when the number of items to be processed increases—in the target trial case, the number of targets—then parallel processing is supported. The most parsimonious conclusion is that in the regular single-target paradigm, processing is still parallel but in that case, limited capacity. With extremely simple stimulus items, for example, as employed in certain of the conditions of Treisman and Gormican (1988), the other reaction time methods seem most apt to provide additional evidence. Both the confusion paradigm (Method VI) and the second response paradigm (Method V) postulate that the items to be processed are composed of constituent information that may be partially processed (e.g., features, dimensions), which may not be the case for search for a long line among a number of other short lines (as in Treisman & Gormican, 1988). The factorial strategy may provide one mode of attack. Most theoretical results have been derived for forced *exhaustive* serial or parallel processing, that is, where the subjects must process all items in order to make a correct response (Sternberg, 1969; Townsend & Ashby, 1983; Townsend & Schweickert, 1985). However, as noted earlier Townsend and Nozawa (1988) recently developed comparable theorems for minimum processing times. Little has been accomplished for self-terminating processing with single targets, but this should not prove difficult.

If one requires evidence about the serial vs. parallel question when the set size is large, then a reasonable application of the factorial method would be to arbitrarily or randomly divide the items into two groups. These two groups would receive manipulation of some factors, such as brightness and spatial separation, that affect processing speed. This parallel-serial test can be applied for any given set size, thus avoiding the artifact associated with set size.

A variation of this paradigm that is of some interest would be to place the two groups of items in separate spatial or temporal locations. In principle, all items could be factorially manipulated, but that would only be feasible with a relatively small number of stimulus items. Subadditivity with regard to the factorial manipulation on "no" trials would support parallelity (e.g., Townsend, 1984; Townsend & Ashby, 1983, pp. 373-375; Townsend & Schweickert, 1985) in this context. Superadditivity would support an architecture that is neither serial nor parallel (Schweickert & Townsend, 1989; Townsend & Schweickert, 1985). Additivity would support seriality.[8] As far as the author is aware, factorial methods have not so far been applied in the ways discussed in this and the previous paragraph.

Another appropriate strategy might be PST, the parallel-serial tester (Method II). In an application to the multi-item search experiments, there would again be a division of the stimulus set into two groups of items. For instance, the investigator might divide a visual array into a left vs. a right segment. In PST either the right or the left side or both could contain a target. Three different conditions impose different response requirements on the subject, but with the same type of stimuli. As noted earlier, the theoretical findings imply that sums of average reaction times from certain conditions must be equal if processing is serial, but not if processing is parallel. Further, they guarantee that perfect or near perfect fits to data could not be simultaneously attained by both types of models.

On more complex items, those made up of several dimensions or features, the accuracy or reaction time methods presented above may be equally attractive. Of course in most cases, which is most appropriate will be dictated by the topic under study. Nevertheless, it is an interesting question as to whether the outcomes of accuracy and reaction time methods, even within the same type of stimuli and response instructions, will yield the same conclusions. Sometimes a general theory can predict what should be the case, and then appropriate specific tests can be applied.

Solving the Parallel vs. Serial Dilemma

One often hears the question asked as to whether the parallel-serial question has been, or can be, "solved." Clearly the issue cannot be resolved by any mathematical work alone. However, mathematics with the proper empirical interpretation has the potential to at least demonstrate what cannot work, and with a little luck and perseverance, to offer experimental designs that may be able to answer the theoretical question being posed.

Occasionally, psychological intuition alone can lead to a paradigm that tests most models of two opposing principles against one another. Even in such cases, it is reassuring to see the reasoning backed up by mathematical demonstration. This can show: (a) That the experiment really can test the two principles, rather than being confounded with another third issue, such as the capacity question in the parallel-serial controversy, and (b) That large classes of models based on the two principles are tested as opposed to rather special cases. For instance, it was comforting to find that PST (Method II) could settle the parallel-serial question in a way that did not depend on particular probability formulations of the models (Townsend & Ashby, 1983, Chapter 13). A rigorous mathematical formulation may also aid in statistical testing and other facets of the overall procedure. Of course, whether in a verbally based or a mathematically derived method, the paradigm must be implemented in the crucible of experimentation.[9]

Even if a paradigm is capable of providing an answer to the serial-parallel question, and tests are carried out with due attention to initial and boundary conditions, statistical rules and so on, we still cannot guarantee the answer to be anything but local. In psychology it is rare that changing the circumstances just a little bit does not alter the results, and sometimes the

8. (a) Strictly speaking, with a sizeable class of processes called Embellished Wheatstone Bridges, the two processes under study must at least lie in two separate subgraphs of processes which are themselves connected by a single "path." A special case of this is serial processing per se where the two processes lie in a single serial chain of processes. (b) Differential parallel vs. serial predictions can also be made for target present trials even if processing is self-terminating (Townsend & Nozawa, 1988).

9. Unfortunately, there seems to exist a wall between the more qualitative and the more quantitative theorists that has not been completely permeable. The more qualitative theorists often state (privately) that they attempt to read the pertinent mathematical approaches but find much of it too abstruse. Similarly, quantitative theorists frequently claim to attempt to write in such a way as to communicate to the other group. It appears that even more effort should be made on both sides to penetrate this barrier.

psychological processes underlying them. Yet, there is reason to believe that many local settings should provide answers to questions about processing if they are put in the right fashion. Of course, in certain settings the background theory predicts that two different environments, types of stimuli, or instructions, processing will be parallel in one, serial in the other. For instance, processing complexity seems to be one determining factor of whether operations can be parallel (and sometimes of unlimited capacity) rather than serial. Some of the Snodgrass and Townsend (1980) results with PST, mentioned in the context of Method V, seem to be of this sort, and complexity plays an explicit role of this nature in the Treisman line of research (e.g., Treisman & Gormican, 1988).

But what if significant generality of mechanism is, as most would hope, a real possibility in psychology? Is then the optimal approach for making progress in psychology, the critical testing of important issues like parallel vs. serial processing? (See also, Massaro, 1987; Meyer, Yantis, Osman & Smith, 1984; Miller, 1982; for other recent examples of testing opposed binary concepts.) Or is it better to formulate a model that is based on specific choices on such issues, for example parallel, exhaustive, independent processing, but perhaps with sufficient complexity and parameters that it can be probed in a broader set of experiments? In the opinion of the author, these two strategies should be complementary. Indeed, in a complex young field like psychology, it would seem foolish to concentrate only on one to the neglect of the other. Each strategy has advantages in regions where the other has weaknesses.

In any event, the availability of experimental methods that can test serial against parallel processing may offer some hope for resolving other tough issues as well.

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