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The Serial Process In Visual Search

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The conditions for serial search are described. A multiple target search methodology (Thornton & Gilden, 2007) is used to home in on the simplest target/distractor contrast that effectively mandates a serial scheduling of attentional resources. It is found that serial search is required when (a) targets and distractors are mirror twins, and (b) when the search elements lack the Gestalt property of intrinsic orientation. The finding is put into the context of Feature Integration Theory (Treisman & Gelade, 1980) that first identified the occasions of serial search to be important to object perception and understanding.

Keywords: attention, visual search, perceptual organization, Gestalt

A problem that has been central to the study of visual attention since its inception is how its resources are used during search for a prescribed and known target. Common everyday experience suggests that attention is quite flexible and is sometimes used in a parallel fashion, while on other occasions there is no recourse but to hunt and peck. It is evident that visual attention must be largely parallelized in view of the fact that boundaries of objects and groupings of objects are perceived as such. The circumstances requiring a serial process are less obvious.[1] It was in this context that Feature Integration Theory (FIT) (Treisman & Gelade, 1980) made a signal contribution by framing the problem of resource allocation in terms of the binding problem (Treisman, 1998). FIT conjectured that binding and serial search went together, that serial search was an outcome of the registration that must occur when multiple features are perceived as being spatially and temporally coincident as occurs in ordinary object perception.

The critical test for FIT was the conjunction search in which elements were defined on two feature dimensions in such a way that no single dimension could be used to distinguish targets from distractors. Early results on the conjunction search suggested that it was serial (Treisman & Gelade, 1980) in so far as reaction time latencies (RT) for deciding target presence increased with the number of nontarget (distractor) elements. Subsequently Townsend (1990) pointed out that such set-size effects on RT are not diagnostic of the serial process because limited capacity parallel processes may have a similar phenomenology.[2] There are now several lines of evidence that the conjunction search is not conducted in a serial fashion despite its apparent difficulty (Thornton & Gilden, 2007; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). The implication is that conjunctions do not involve binding in a way that is exhaustive of attentional resources.

FIT was also criticized for its reliance upon the notion of primitive features and for imposing a dichotomy in search difficulty; features are easy whereas conjunctions are hard. Relevant to the first issue is evidence that search appears to operate at a level of object description that is sensitive to aspects of scene construction that are in no way primitive. Two examples that are known to influence search for line drawings are the formation of illusions (Rensink & Enns, 1995) and the appreciation of perspective (Enns & Rensink, 1991). Although it is true that search for objects differing on some primitive feature may be highly efficient, the class of efficient search is much broader and in fact has never been completely characterized. The second issue concerns the finding that search difficulty is patently a function of distractor homogeneity and target-distractor similarity (Duncan & Humphreys, 1989; Humphreys, Quinlan, & Riddoch, 1989). This perspective replaces the two-level ontology of feature primitives and feature conjunctions with a framework in which search difficulty is graded by what is essentially a signal-to-noise ratio. Continuous attributes such as homogeneity and similarity do not invite a mapping into a "serial/parallel" processing distinction, and as the signal detection perspective provided a better picture than FIT of what makes search difficult, the distinction was generally abandoned in favor of continuous constructs such as capacity limitation and efficiency.

In fact, the issue of whether there is such a thing as serial search in the sense intended by Treisman and Gelade (1980) was not experimentally accessible in the absence of methodology that could distinguish between severe capacity limitation and true seriality. Thornton and Gilden (2007) developed a search technology that met this requirement by first employing a multiple target search method (first described by van der Heijden (1975) and

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[1] In so far as eye movements enforce a type of seriality, this problem is typically formulated in terms of searches that do not require eye movements and where shifts of attention are covert, decoupled from gaze.

[2] Parallel processes might also run slower when inspecting larger sets if they are capacity limited. The notion here is that dividing a finite resource over multiple inspection subprocesses might lead to each slowing down if the resource is rate determining. Consequently, there is no simple and reliable way of inferring how attention is being used from the mere presence of set-size costs in the time to find a target.

brought to our attention by Townsend (1990) as a potentially useful methodology for dealing with capacity limitation), and then by formalizing the usage of attention in terms of explicit computational models. Several instances of serial search were found among a large test-bed of search tasks, and we now possess key diagnostics of both serial and parallel process within the multiple target search method. In this article, we use these diagnostics in a plodding but ultimately successful definition of the class of serial searches. Here we demonstrate that serial search turns on a rather subtle aspect of Gestalt having to do with the way objects often appear to face or point towards a given direction. The evidence will be presented after a brief review of how it is possible to make the serial/parallel distinction in the first place.

Diagnostics of Serial and Parallel Process

Thornton and Gilden (2007) reported data from 29 multiple-target search studies that covered a wide range of search difficulty, from simple feature searches to the most difficult spatial configuration searches. We found, as did Wolfe (1998) who also examined a large body of data, that visual search data can be broadly grouped into three classes: (a) easy (feature contrast), (b) hard (conjunction of features and some spatial configuration contrasts), and (c) quite difficult (rotation direction, the most demanding spatial configuration contrasts). Figure 1 (Figure 9 in Thornton & Gilden, 2007) illustrates how these classes appear within the perspective of the multiple target experimental design. The classes are in part defined by the usual metric of difficulty; target-present slope, evaluated in this design over cells where there was exactly one target. The search difficulty subjectively increased in the order A, B, C, and the one-target cells yielded RT/set-size slopes of, respectively, 11, 30, and 51 ms per item. The shallow slope in Panel A of Figure 1 is itself suggestive of parallelism, a conclusion reinforced by the redundancy gains in RT on the pure target trials (those trials with no distractors).[3] The simple feature searches summarized in Panel A are not of interest here as these are of the "pop out" variety, and are obviously searched for in a parallel fashion. More interesting and more problematic are the difficult searches illustrated in Panels B and C, and sorting these out required the full power of the multiple target method.

Our version of multiple target design involves three levels of set-size that together generate nine distinct combinations of target and distractor number. As each of these cells has an associated mean RT and error rate, each cell presents an opportunity for setting a speed-accuracy trade-off function. The inherent complexity of the design requires a method of data analysis that captures both how attentional resources are scheduled as well as how speed-accuracy trade-off is negotiated as a function of work load (set size). Our approach has been to build sequential sampling models of the search process (Laming, 1968; Link, 1975; Ratcliff & Smith, 2004; Townsend & Ashby, 1983) and to allow the trade-offs to be set through Monte-Carlo simulation of the observed data. Simulations of parallel and serial architectures led to two diagnostics that replace elementary analysis of set-size effects on RT.

Diagnostic 1: Speed-Accuracy Trade-Off

One of the more interesting aspects of the data in Figure 1 is that the target-absent RT set-size trends (the dashed line in RT) are quite shallow. In the easiest searches, (A) the trend is negatively sloped, in the intermediate difficulty searches (B) the trend is flat, and in the most difficult searches (C) the target-absent trend still manages to be less steep than the single-target trend. It might be expected that the complete absence of targets would require more time to verify than the presence of any target, and such would be the case were observers exhaustively searching displays with an unwavering criterion for categorizing elements as targets or distractors. These trends rather imply that the responses on target-absent trials are critically influenced by a speed-accuracy trade-off. The costs incurred are increases in the miss rate, particularly on displays that have only one target. The benefit is that the observer is able to maintain fast responding on the most difficult trials.

The manner in which the trade-off is made is diagnostic of process. Parallel processes generally are able to negotiate speed and accuracy with better economy than serial processes. The principal reason for this is that a parallel process might be able to determine relatively quickly if the early returns of perceptual samples contain any suggestion that a target is present. Even if that suggestion is in error, a parallel procedure always has some information about every element. Serial processes are inherently slower and more error-prone because they may have no information whatsoever about a particular element until relatively late in a search. When a serial process terminates a trial based on partial information, it does so at considerable risk. Examples of favorable trade-off positions are evident in Panels A and B. In Panel A, the target-absent latencies actually decrease with set-size at a cost of only a few percent of missed targets. In Panel B, the trade-off is still quite favorable; a few percent missed targets buys a target-absent function that is flat with set-size. Such economy suggests that the data in Panels A and B were produced by a parallel process. Panel C, in contrast, illustrates a substantially poorer trade-off. These searches suffered considerable slowing with set size on target-absent trials even though severe costs were incurred in missed targets. Slow and error-ridden performance is the hallmark of the serial search process. Nevertheless, it is not possible to stipulate that the trade-off in Panel C is inconsistent with parallelism without resort to extensive model fitting that takes other trends into account. For this reason, the trade-off point is best used as a diagnostic in the presence of other pieces of evidence.

Diagnostic 2: False Alarm Trends

Casual inspection of the false alarm trends in Panels A and B of Figure 1 (the dashed line in error rate) reveals a second oddity; the

[3] There are several ways in which multiple targets might lead to redundancy gains. First, there are statistical race gains (Raab, 1962), the fact that the distribution of winning (fastest finishing) times always has a shorter mean than the distribution of finishing times for any individual competitor or process. Race gains are relevant if search decisions (target or distractor) are made independently for each element. Redundancy gains may also arise from a decision process that is not concerned whether any particular element is a target, but rather if any elements are targets. A decision maker that has access to the partial results of each element analysis might infer that targets are likely present even if no single process has yet run to completion. That is, if every element looks target-ish, then it is unlikely that every single one of them is a red-herring—the more so as the number of targets increases.

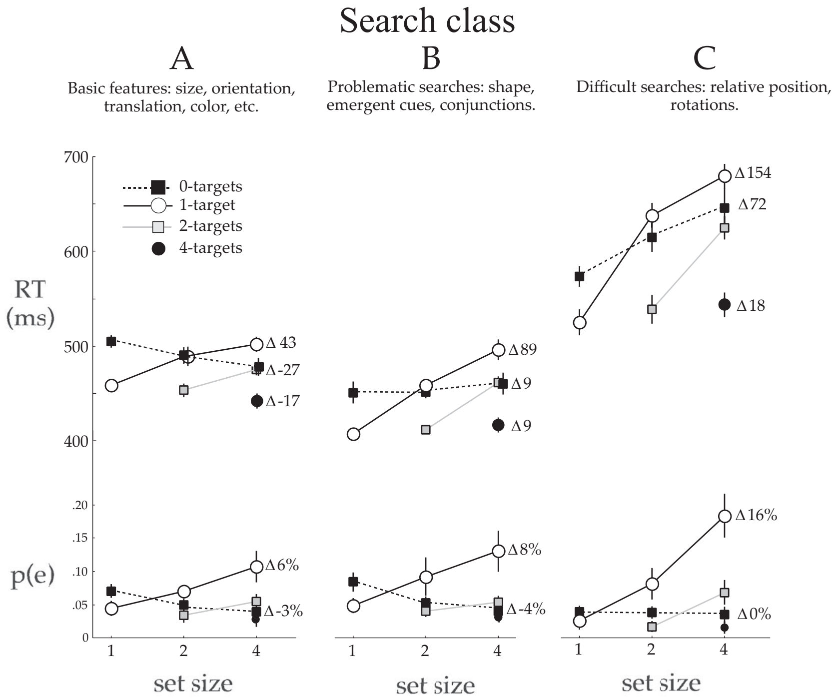

Figure 1. The three basic patterns of data in multiple target search. Classes A, B, and C correspond to searches that are, respectively, parallel with little capacity limitation, parallel with moderate to high capacity limitation, and serial. Inset numbers of the form ΔN give gains and losses in RT and error rate computed at set-sizes 1 and 4. Dashed lines indicate target-absent trials.

trends are negative. It might be expected that where there are more opportunities to make mistakes, more mistakes would be made, a statistical truism commonly known as probability summation. Here the mistake is in categorizing a distractor as a target and such mistakes would be expected to increase with set-size on the target-absent trials. Evidently, this is often not the case in practice. Observers might circumvent probability summation if they required greater certainty about target identification at larger set size. This hypothetical strategy, however, is not consistent with the observation that people do exactly the opposite, they relax their criteria so that the target-absent trials may be terminated early. This is the logic of the speed-accuracy diagnostic described above. There is a second mechanism available to parallel processes that also avoids probability summation. In formal theories of the parallel process, the principal effect of dividing attention is to slow the rate at which each subprocess accumulates information about the element it is responsible for. If slowing is accompanied by increased accuracy, the trade-off might be sufficient to countervail the effects of probability summation.[4] The serial process, in contrast, does not suffer the effects of divided attention, and presumably runs at the same rate as it operates on each element in turn. Therefore, the serial process cannot benefit from this second form of speed-accuracy trade-off, and it is fully exposed to probability summation effects at larger set size. The only way that a serial process can avoid increasing false alarms with set-size is to set the target criterion so high that the false alarms are close to zero throughout the design. Note that in Panel C we observe the lowest level of false alarm rates even though these are the most difficult searches.

The false alarm trends are generally sufficient to decide the nature of any given search. In Thornton and Gilden (2007) and in the data reported here, it is the case that parallel models have greater likelihood given the data when false alarms drop by more than a few percent, and serial models have greater likelihood when the false alarms are relatively flat. For this reason, we shall focus on the false alarm trend throughout the experimental work described here in deciding which searches are conducted in serial and which are conducted in parallel.

Definition of the Simplest Serial Search Task

There is one regime where search must be serial: that where the targets and distractors differ only in minute detail. This class is of infinite size, there being an infinity of small distinctions. For example, the search for an n-gon among n + 1-gons is serial for some n. It is not clear that this regime provides particular insights into either object understanding or attention, but the study described by Cousineau and Shiffrin (2004) does provide an instructive example of the type of data that might be observed at low discriminability. In their study the elements were multi-spoked

[4] This mechanism is only expected to operate when divided attention leads to slowing consequent to capacity limitation. When capacity is not a critical factor in the rate at which perceptual samples are obtained there will be less movement along the speed-accuracy trade-off curve with set-size. For the simplest feature searches with the least capacity limitation the false alarm rate is replaced by redundancy gains in RT as the key diagnostic of process.

objects that were constructed with the specific intention that it would be difficult to ascertain whether any given object was a target or distractor. The data arising from the target present trials was undeniably produced by a serial process; the reaction time distributions were multimodal with humps specifying whether the target was found on the first, second, third, or fourth element inspected. The fact that Cousineau and Shiffrin can read the traces of the serial process directly from the RT distribution is an elegant demonstration of how difficult search is in this regime.

The theoretically important case involves serial search for elements that are both easily categorized and discriminated. This is the case addressed by FIT in conjunction search and is largely the reason it has been so influential. Conjunction searches are difficult not because the elements require detailed inspection to figure out what they are, but because different distractors share feature values with the target on different perceptual dimensions. The cross-dimensional aspect of feature sharing leads to very effective camouflage when a collection of distractors is present. In this sense, the question raised by FIT was whether the kind of group camouflage that is achieved through feature conjunction mandates a serial inspection process. We found that it does not (Thornton & Gilden, 2007), rather the conjunction form of group camouflage induces capacity limitation in a parallel process. This finding, however, does not imply that the serial process will not be found in other forms of group camouflage.

The same methodology that clarified the nature of conjunction search also led to the first positive instances of serial search in a group camouflage context. We found that the key signatures of serial search (slow and error ridden target-absent judgments, flat and low false alarm rate functions of set-size) were often observed when targets were mirror images of distractors. Mirror twins may be quite easily categorized as targets and distractors, and when they do lead to serial search, it need not be because of intrinsic category confusion as in the Cousineau and Shiffrin task. To a large extent, this finding defines a minimal condition for serial search through group camouflage. Mirror reflection is a 1-bit transformation, and it is not possible to pose a simpler rule-based distinction. Unfortunately, this distinction is not sufficient as Thornton and Gilden (2007) also found numerous examples of mirror twins that could be searched for in parallel.

Figure 2 offers examples of both serial and parallel processes in data from studies that used mirror reflection to define search elements (taken from Thornton & Gilden, 2007). Data from "o +" and Y-junction studies are displayed, the targets and distractors being shown above the appropriate RT and error rates. From the full design of nine cells, we have plotted the six most relevant for distinguishing parallel from serial process: the 1-target and 0-target cells. The Y-junction data show a key signature of parallelism by having a 6% *drop* in error in the false alarm trend across set-size. In contrast, the "o +" search shows the set-size independent low false alarm rates that results from a high-threshold serial search. In support of this classification, there is also evidence from the way target-absent RT trades off with the 1-target miss rates. The "o +" target absent RT increases about 50 milliseconds over the range of set-size even when the miss rate approaches 30% at a set-size of 4. A better trade-off is realized by the Y-junction where the target-absent set-size costs are 20 milliseconds in RT and 15% in the 1-target miss rate. In summary, these data indicate that there is some aspect of object form beyond mirror reflection

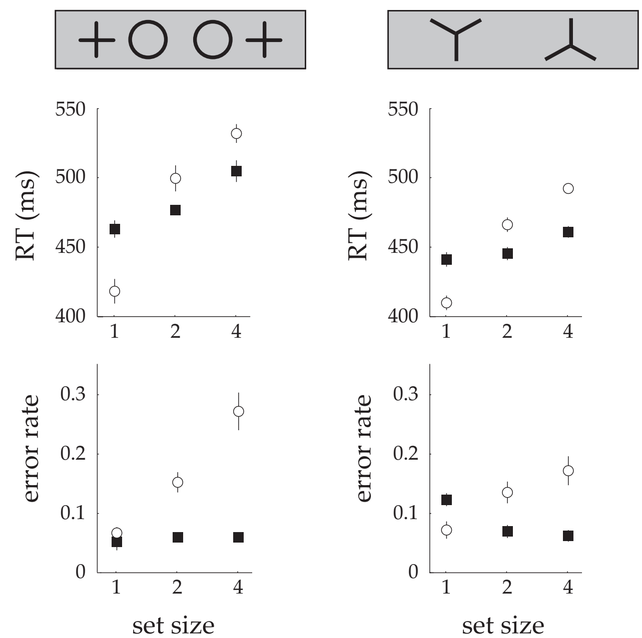

Figure 2. RT means and error rates for "o +" and Y-junction in multiple target search among mirror twins. Only the most informative trends are plotted: open circles show data drawn from trials with a single target, filled squares show data from trials with no targets. This convention will be followed in all figures. The key diagnostics here and elsewhere are (1) The slope of the false alarm trend with set-size, and (2) The degree to which missed targets offset the RT costs on target absent trials.

symmetry that leads to serial search in a group camouflage context. The following experiments were conducted to determine what this might be.

Experiment 1: Element Connectedness and Mirror Orientation

There are a number of dimensions over which the elements "o +" and Y-junction differ from each other and differ from their mirror twins. For one, the Y-junction is a connected form, the "o +" is not. This is potentially an important difference because connection invites strong grouping (Palmer & Rock, 1994). It is quite possible that the "o +" is better camouflaged through spurious groupings based on common shape because the two pieces—"o" and "+"—do not bind together into a coherent target. Secondly, the mirror planes of Y-junction and "o +" are orthogonal, a distinction that might be relevant in view of the fact that orientation has a variety of consequences for visual perception. The horizontal-vertical illusion is a common example of the perceptual distinction between left-right and up-down orientation. If it is the orientation of the mirror plane that makes 'o +" serial, then a rotated Y-junction might produce a serial search. In this study, disconnected Y-junctions were presented in both orientations to see if either distinction is potent in creating a serial search. To promote the possibility of creating a serial search the Y-junctions were also bi-colored so that their different elements tended to form spurious groupings based on common polarity.

Method

Participants. Eight undergraduates at the University of Texas participated in each of the two studies. All had normal or corrected vision and were given course credit for participation.

Stimuli. Search displays were constructed in the same manner as the 29 studies described in Thornton and Gilden (2007). Displays contained either 1, 2, or 4 elements.[5] We use small set sizes to avoid visual artifacts caused by overcrowding (masking) and by loss of acuity in the periphery (Geisler & Chou, 1995). Individual elements were configured about a central fixation point along a virtual circle whose radius varied between experiments from 1.5 to 2.5° of visual angle at a viewing distance of 57.3 cm. Individual Y-junctions subtended 1.2°. Their orientations and coloring as they appeared in the two studies is illustrated in Figure 3. Elements were drawn at canonical locations along the virtual circle (+45, −45, +135, −135°), and the entire display was randomly rotated about fixation to remove configural effects by choosing a uniform deviate from the interval ±25°. Additional radial jitter (~.5°) was added individually to each element to remove effects due to element co-linearity. In all, there were nine basic types of stimulus displays; displays containing three targets were excluded from this design. Displays consisted of all distractors (target-absent trials), all targets (*pure-target-present* trials), or some combination of a variable number of targets and distractors (*mixed* target-present trials). At each set size there were equal numbers of target-absent and target-present displays (the full matrix with detailed discussion is given in Figure 2 of Thornton & Gilden, 2007).

Procedure. Observers were situated comfortably at the desired distance of 57.3 cm in mesopic viewing conditions. They each completed eight blocks of 144 trials. Their task was to press "1" on a keypad if there was at least one target present, "2" otherwise. Trials were paced so that 250 milliseconds elapsed between response and the presentation of the subsequent trial. Participants were given one to three practice blocks of 50 trials before the collection of data so that they could bring their performance into the range of 5 to 10% error. A fixation cross was present on all displays that oriented the observer's gaze throughout the study. Observers were instructed to maintain fast but accurate responding. In this paradigm, response latencies are sufficiently brief that the role of eye movements is minimized. No feedback was given.

Analysis. Reaction times were treated as outliers and removed if they were greater than three standard deviations beyond the mean or less than 200 milliseconds. In no case was more than 1% of the data excluded. Before averaging, RT data from individual observers were converted to z-scores using each observer's global mean and standard deviation. After normalization to z-scores the within-observer RT medians for each of the nine search cells were computed. Median z-scores were used to compute cell means and standard errors across observers. For clarity of presentation and intertask comparison, the final averaged RT z-scores and standard errors were converted back to units of milliseconds using each task's global RT mean and standard deviation (averaged over observers). This last step is simply to present our results in dimensional units and in no way influences the shape of RT or error trends. The same stimuli, procedures, and analysis techniques were used in Thornton and Gilden (2007).

As one of the key diagnostics of process is the false alarm trend with set-size, we will in each experiment be evaluating the magnitude of this trend and whether the magnitude is discriminable from zero. Here the trend will be calculated as a linear trend with weights [−1, 0, 1] applied to the set-size conditions [1, 2, 4]. This weighting treats the conditions as if they were equidistant, which they are in the logarithm, but no conclusion presented in this article is sensitive to this constraint.

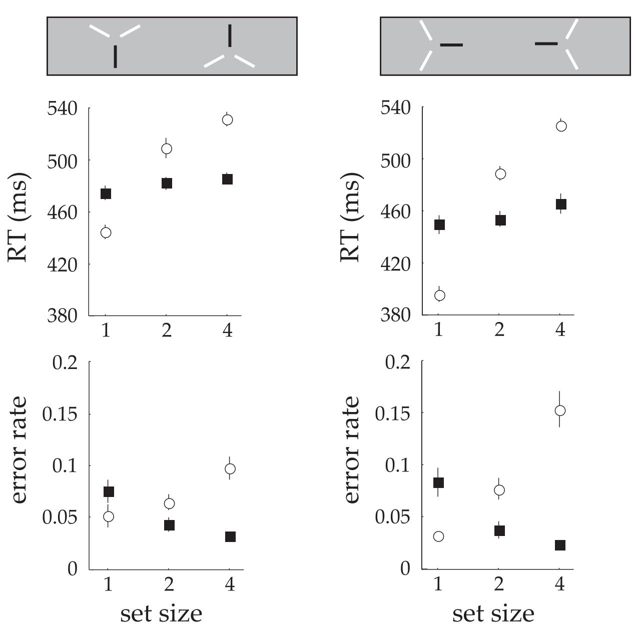

Figure 3. RT means and error rates for two orientations of bicolored and disconnected Y-junctions in multiple target search among mirror twins.

Results and Discussion

Observer averaged latencies and error rates are illustrated for the two studies in Figure 3. At a glance, it is clear that no manipulation in this study succeeded in producing data consistent with a serial process. In fact, all three versions of the Y-junction (upright Y, both orientations of disconnected Y-junction) show the data patterns diagnostic of the parallel process. All have decreasing false alarms with set size ($t(7) > 3.5$, $p < .005$, for both orientations shown in Figure 3), and all have virtually flat target-absent RT functions that are incurred with moderate 10 to 15% penalties in 1-target miss rates. Reversal of probability summation and good trade-offs are consistent only with a parallel process (Thornton & Gilden, 2007). From these data we can conclude that "o +" symmetry plane is not what makes mirror reversal search data

[5] Although a maximum set size of 4 is small by comparison with that typically encountered in the singleton search method, in multiple target search it is adequate to expose all of the necessary set-size trends. Generalization of our results to larger set sizes is not an issue in this work as we are seeking the serial process. The presumption has historically been that attentional resources are used in parallel in small clumps but perhaps serially between clumps (Pashler, 1987). To be specific, we seek to find the serial process that operates at the smallest level of clump, the individual element.

serial. If this were not true then the rotated Y-junction would have been serial. We can also conclude that disconnection does not necessarily generate serial mirror inversion searches. Similarly, whatever false groupings were promoted by bicoloring the junctions were not sufficient to make the searches serial.

Experiment 2: The Venus Symbol in Visual Search

All of the results from Experiment 1 appear to flow from the simple fact that rotation, bicoloring, and disconnection do not profoundly change the underlying percept of the Y-junction. The stimuli illustrated in Figure 3 look like Y-junctions, and they generate Y-junction search data. Although this observation is simplistic, it is also instructive, and it motivated the inquiry that ultimately led to understanding what makes "o +" a stimulus productive of the serial process. This inquiry began with the recognition that "o +" does not really look like one thing, it looks like two things that happen to be nearby each other. Yet, "o +" could be made to look like something were the two parts connected. Indeed the connected version "o+" is a recognizable symbol, the Venus symbol, which is turned on its side. The fact that "o+" is sufficiently coherent to be a namable symbol, whereas "o +" is just two other symbols that happen to be next to each other provided ample motivation for a Venus symbol mirror search experiment. Were it possible to parallelize visual search by simply connecting the two pieces we would have the beginnings of a fruitful distinction. At the very least, we would have found a very simple switch for toggling between serial and parallel processes.

In a companion study, we also replicated the disconnected Y-junction search using mono-colored stimuli. Replication of this important stimulus gives us assurance that the methods are sound and the data reproducible.

Method

The general procedure, data analyses, and observer pool used in the two studies was identical in every way to those described in Experiment 1 and in the 29 studies reported in Thornton and Gilden (2007). Eight different observers participated in the two search tasks. The only differences were in the stimuli used, and these are drawn in Figure 4 exactly to scale.

Results and Discussion

The mean latencies and error rates for both disconnected Y-junction and connected "o+" are displayed in Figure 4. It is immediately apparent that the false alarms in the two studies dropped with set size ($t(7) > 3.4$, $p < .006$, for both). This is the most robust signature of parallelism that exists in the multiple target methodology, and it implies that the Venus symbol permits a parallel search. It is equally true from the Y-junction data that connection *per se* is *not* the relevant distinction. To be clear, the Venus symbol inherits something from connection that changes the nature of visual search from serial to parallel, but it is not necessary that a search element be connected for mirror reversal search to be parallel. Discovering the nature of this inherited property was the goal of the following experiments.

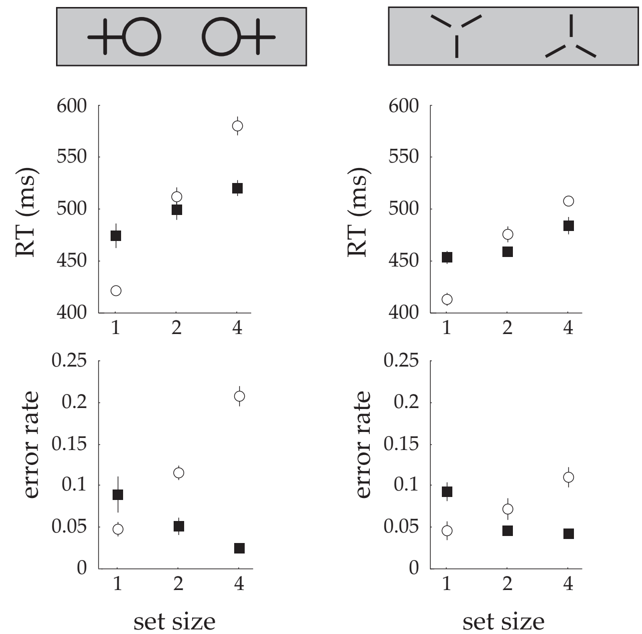

Figure 4. RT means and error rates for the Venus symbol and a disconnected Y-junction in multiple target search among mirror twins.

Experiment 3: Gestalt Properties—Tops, Bottoms, Fronts, and Backs

A key property of many figures is that their appearance, literally, what they look like, depends critically on how front, back, top, and bottom assignments are made. There are many reversible figures such as duck-rabbit that highlight this perceptual fact by providing two equally compelling interpretations and a sense of wonderment as they emerge within their respective contour assignments. Objects that have fronts and backs are accompanied by an attendant sense of facing or in some special cases, pointing. Percepts of facing, pointing, or having tops and/or fronts are instructive examples of perceptual organization, and obvious only once pointed out. In this vein, Wittgenstein can seriously entertain the question: "How does it come about that this arrow → points? . . The arrow points only in the application that a living being makes of it" (Wittgenstein, 1958, p. 132). The "how does it come about" question is subtle indeed and has been a steady source of productive inquiry (Attneave, 1968; Palmer, 1980). Regardless of how such percepts arise, that they do arise appears to be important in framing the circumstances of serial visual search.

One of the senses in which the Venus symbol looks like some one thing whereas "o +" looks like two things is in the way the Venus symbol emerges with a top and bottom. In the Venus symbol the "o" is the head, the "+" is the body, and the two together make a unitary symbol. The Venus symbol is normally presented in an upright orientation with the head above, but it is not necessary that the symbol be right-side-up to maintain the percept of the human form. In the reclining position, "o+", the head is still on top of the body, the body composition not being tied to an environmental axis. The form "o +," in contrast, does not have a head and body. Simply, "o +" is a juxtaposition of two symbols that are coherent within themselves but bear no relation to each other except that of proximity. Presumably this is because the parts of "o +" are individually complete in the sense of being "good" forms (Garner & Clement, 1963). That they are individually complete leads to a kind of stalemate where the two forms share a "next to" relation without one being on top or in the front.

The difference between being merely "next to" and "being on top" is most easily articulated through a distinction between extrinsic and intrinsic orientation. This distinction will not only help clarify what is at stake here, it also will create an important link to FIT, the first substantive theory of the serial process. The critical point is that the sole perceptual contrast between "o +" and "+ o" is also the distal contrast, consisting entirely in which part is on the left or right. Left and right (or above and below) are local properties imposed by the placement of a local environmental axis; there is nothing about the element that dictates which part is on which side. It is in the sense that the axis placement and the orientation it imposes is extrinsic to the figure. The Venus symbol, on the other hand, does not require an extrinsic axis to differentiate it from its mirror twin because it comes with its own orientation, the head is on top. This orientation is created by perceptual organization and in this sense is intrinsic to the percept of the figure.

The existence of intrinsic orientation in all of its manifestations (top/bottom, front/back, facing, pointing) appears to explain why some mirror reversal searches are serial and others are parallel. The "o +" is extrinsically distinguished from its mirror twin and search for this form is serial. The Venus symbol has intrinsic orientation and it may be searched for in parallel. Similarly, the Y-junction is also intrinsically oriented and is also searched for in parallel. Where Y-junction differs from the Venus symbol is that disconnecting the spokes of the Y does not disturb the percept of the form as a Y, and the disconnected form maintains both its sense of orientation and its parallelism in search. Why disconnection should affect the Venus symbol so differently is presumably related to the informal notion of pattern goodness. The line elements that compose the disconnected Y-junction look incomplete and invite a perceptual connection. On the other hand "o" and "+" look just fine by themselves and so do not invite completion in a higher order unit. Whatever the explanation, the congruence of what is perceptually self-evident with the search data suggests the following rule:

Conjecture. When targets and distractors are easily categorized, that is, in the regime of group camouflage, visual search is parallel except in the specific case where distractors are mirror images of targets and the search elements have no intrinsic orientation.

This conjecture is equivalent to the following:

Conjecture 2. The placement of an axis that allows extrinsic relations such as to-the-left, to-the-right, above, and below, is local to individual elements. As elements cannot share these assignments in mirror reversal search, extrinsic orientations can only be created one element at a time. Elements that lack intrinsic orientation will therefore lead to serial mirror reversal search.

This second version of the conjecture is closely allied to the core concept of FIT, that the registration of feature maps in feature binding is a one-at-a-time process. FIT and the theory proposed here find the same origin of seriality in visual search in the placement of axes that define local relations. Where the two accounts differ is in the matter of empirically identifying the occasions where such axes are required. FIT imposed axes to nail down feature maps at a point in space. Our conjecture has nothing to do with binding and finds the serial process rather in the inherent locality of relative position.

Support for our conjecture was sought in two additional studies that further delineated the role of intrinsic orientation in mirror reversal search. The first study was modeled after "o +" and consisted merely of substituting figures that had similar symmetries. The second study poses a stronger test and utilizes portraits in a way that would have not been contemplated outside of the framework provided by our conjecture.

Experiment 3a: Square-Asterisk and Radiating Line

The sense that a figure is oriented or points or faces is the sort of subjective matter that is implicit in all Gestalt demonstrations. To construct appropriate tests of our conjecture it is patent that this subjectivity must guide the choice of stimuli. There is no algorithm for strength of facing, for example, and the best that can be hoped for is that the stimulus selection will manifestly have the properties we seek to test. In this experiment, we constructed two types of target element that we hoped would lead to serial or parallel processes depending on whether they, respectively, lacked or had the property of intrinsic orientation. The serial target was an asterisk placed next to a square. In so far as the square has the same symmetry properties as the cross and the asterisk approaches the symmetry of the circle, we thought that it would lead to a serial "o +" type of search. Both the square and the asterisk have the character of "good gestalt" and when placed next to each other their association does appear to be merely that of "next to". A variation of "o +" that we thought might lead to parallel search is "o –". This is a figure that can appear as a line radiating from a circle or alternatively as a lollipop on its side. The two different interpretations have different orientations and the mere fact that they exist entails the figure does have the property of intrinsic orientation.

Method

The procedure, data analyses, and observer pool used in the two studies was identical in every way to those described in Experiments 1 and 2. Eight different observers participated in the "square asterisk" study and seven different observers participated in the "o –" study. Otherwise, the only differences were in the stimuli used, and these are drawn in Figure 5 exactly to scale.

Results and Discussion

The mean latencies and error rates for "square-asterisk" and "o –" are displayed in Figure 5. "Square asterisk" mirror reversal search is clearly serial. The false–alarm trend is virtually flat with an intercept around 3 to 4%, the minimum error that is typically achieved in this design. Over the range of set size the variation is a mere 1%, $t(7) = 1.7$, $p < .07$. In contrast, the false alarms for "o –" clearly decrease with set-size implying that this search is conducted in parallel, albeit with capacity limitation. Here the increase in accuracy from set-size 1 to 4 is 6%, $t(6) = 7.2$, $p < .0001$. Additionally, the two searches produce markedly different trade-off functions between target absent RT and 1-target miss

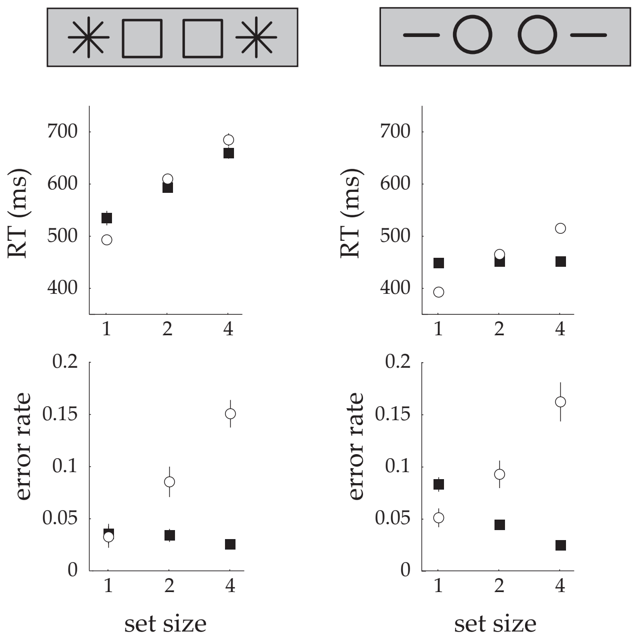

Figure 5. RT means and error rates for "square-asterisk" and "o –" in multiple target search among mirror twins.

rates. At comparable levels of missed targets, the "o –" target absent RT function is flat while the same function for "square-asterisk" increases by over 100 milliseconds. Again, favorable error trade-offs for early termination of target absent trials is diagnostic of parallelism. Referring back to the basic search classes that were found by Thornton and Gilden (2007), it is evident that "o –" is a good example of a search in Class B, searches that are difficult and capacity-limited but parallel. Similarly, "square-asterisk" is a good example of a Class C search, searches that can only be fit by high-threshold serial models.

Experiment 3b: Portraits

Presumably one of the best examples of a shape that faces in a particular direction, left or right, is the human face in profile. In addition, one of the least ambiguous shapes that points neither to the left or right is the human face in frontal view. In this experiment, we used these observations to create a target, two people facing each other, that had a strong sense of directionality. Similarly, we also created a target, two people in frontal view, which created no sense of direction within the picture plane. In a mirror reversal search, the first portrait pair must be surveyed in parallel and the second in serial if the conjecture is true.

Method

The procedure, data analyses, and observer pool used in the two studies was identical in every way to those described in Experiments 1 and 2. Eight different observers participated in the two search tasks. The only differences were in the stimuli used, and these are drawn in Figure 6 exactly to scale.

Results and Discussion

Mean latencies and error rates for both types of portrait pair are shown in Figure 6. The man and woman facing each other show the signs that are characteristic of parallelism; marked decay of false alarms with set-size (5.4% drop, $t(7) = 4.1$, $p < .002$) and substantial trade-off benefits on the target-absent trials (20% error buys a target absent RT function that is no steeper than the target-present function). Similarly, the frontal portraits show all the signs of serial search; relatively flat false alarms (1.2% drop, $t(7) = 2.6$, $p < .02$) and substantial costs in trading for time on target-absent trials (25% error buys a target-absent RT function that is steeper than the target-present function). These are the results required by the conjecture and the conjecture is strengthened by them. Beyond this simple conclusion, it must be recognized that this is a peculiar study, one that would never have been contemplated outside of the conjecture. In this sort of inquiry that is guided only by empirical investigation, the novel prediction is the strongest evidence.

General Discussion

In this article, we claim to have resolved a particular issue in the field of visual search, that of when search is serial in the theoretically important case of group camouflage. This issue has been implicit throughout the history of this field but it could not be addressed without a technology that could disentangle set-size effects caused by serial selection of elements from set-size effects caused by divided attention. All of the evidence supplied here is based on the technology developed in Thornton and Gilden (2007), and the principal force of this technology is that it focused the analysis on the error rates, an aspect of the data that has historically been of little concern. To reinforce the connection between the error rates and the claims we

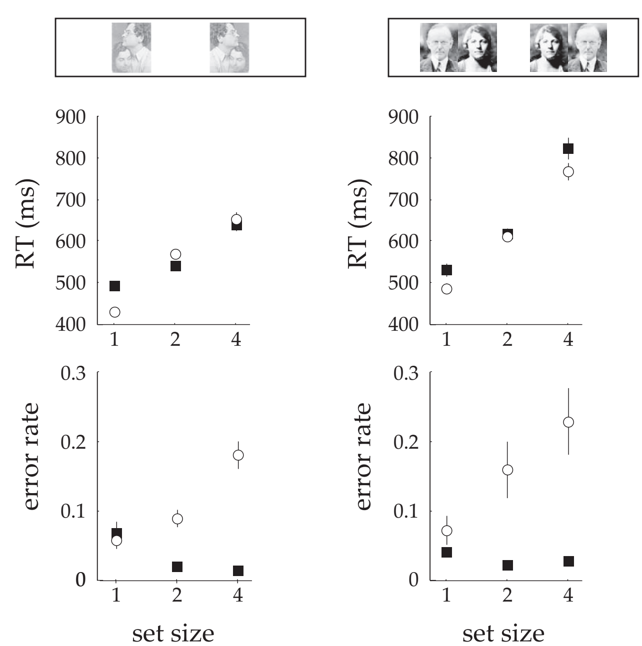

Figure 6. RT means and error rates for two types of portrait in multiple target search among mirror twins.

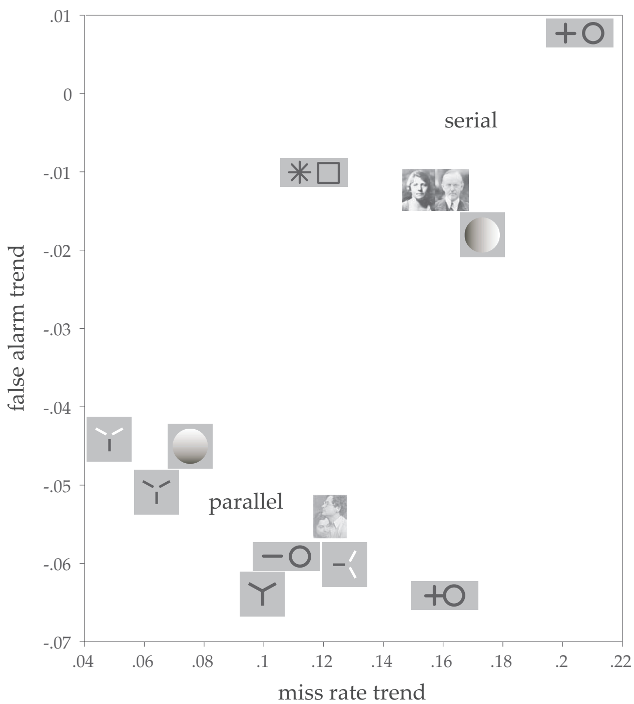

Figure 7. Averaged data from the studies presented here in addition to key studies from Thornton and Gilden (2007) ("o +", Y-junction, shape from shading) are plotted in terms of false alarm trend [false alarm (set-size = 4) – false alarm (set-size = 1)] and miss rate trend [1 target miss rate (set-size = 4) – 1 target miss rate (set-size = 1)]. Each study is depicted by an example of its target.

make here, we illustrate in Figure 7 how the serial processes cluster separately from the parallel processes when viewed in terms of false alarm and miss rate trends. Admittedly, the miss rate trend is only one half of the speed-accuracy trade-off affecting the target-absent trials, but large miss rates tend to be associated with steep RT trends in the most difficult searches and this variable can more or less stand in as an index for the costs incurred by early termination. Figure 7 makes clear that the presence or absence of intrinsic orientation determines whether or not the search is in the serial cluster, and further that this cluster occupies a relatively compact region of poor trade-off and high threshold for signaling a false alarm.

Figure 7 includes two studies from Thornton and Gilden (2007) that help illustrate the utility of the distinction between intrinsic and extrinsic orientation. The phenomenon of interest is the extraction of shape from shading. The instance we consider is drawn from Kleffner and Ramachandran (1992) and involves the perceptual fact that an aperture bounded light-dark gradient generates a vivid three-dimensional shape when the gradient is aligned vertically in the picture plane; one sees either bumps or dimples depending respectively on whether the lighter parts are located at the top or bottom of the aperture. When the gradient is aligned horizontally, the apertures appear to be flat. That the percept is three dimensional only when the gradient is vertical implies that the visual system is prepared to infer the presence of an overhead light source (although the preferred direction is not directly overhead and there is a dependence on handedness [Sun & Perona, 1998]) but is unwilling to infer a source of illumination located either to the left or right in the picture plane.

Mirror inversion search using singleton designs (Kleffner & Ramachandran, 1992) produced data in experienced observers that was consistent with the manifest experience that bumps are strongly segmenting from dimples; the vertical gradients had flat RT functions with set-size whereas the horizontal gradients produced positively sloped trends indicating lower efficiency. Thornton and Gilden (2007) took the vertical/horizontal distinction beyond relative efficiency by showing that the horizontal gradients lead to searches that are not merely difficult, they are demonstrably serial. From the perspective of the present work we can now understand why this is so. A light-dark gradient has no intrinsic orientation; it does not face in a particular direction, it does not point, nor does it have features that designate a top/bottom or front/back arrangement in the sense, for example, that the head is on top of the body. Therefore, in the case where the gradient is horizontal each aperture acquires spatial assignments of to-the-left and to-the-right through the relations imposed by a local axis. These assignments are examples of extrinsic orientation and that they can only be created one a time leads to serial search. However, when the gradient is oriented vertically the perceptual assumption of an overhead light source produces a critical change in the nature and number of organizing axes. Instead of each aperture defining its own local coordinate structure, all of the apertures are perceived to be embedded in a common space. This space has the coordinate structure endowed by an overhead light source and all of the apertures within the space inherit this geometry regardless of whether their gradients increase towards the light or away from it. Differences in the gradient direction is resolved in the third dimension through the percept of bumps and dimples. Bumps and dimples point in and out of the picture plane and so have intrinsic orientation. In this sense, the inference of overhead light source is able to transform a multiplicity of extrinsic relative position assignments into a multiplicity of oriented convex and concave shapes.

We conclude with a final observation that relates the present work to earlier findings having to do with mental rotation. Hinton and Parsons (1981) conducted an intriguing study that led to the definition of the minimal properties of an imagined image that permit mental rotation. In their version of the task, letters appeared at various angles of rotation, and people had to decide as quickly as possible if they were mirror inverted. Shepard et al. had previously shown that prior knowledge of the angle of the test stimulus had no influence upon the well-established tent-function in reaction time, if there was not also prior knowledge of the test letter identity (Cooper & Shepard, 1973). Were the angle at test by itself useful information, then observers could have mentally rotated an imagined figure before the appearance of the test letter and so could have saved substantial amounts of time in deciding if the test were mirror inverted. In other conditions where the letter identity was known, such strategies were routinely observed. This finding implied that a mental rotation transformation has to transform something, and that without the letter identity there is nothing for the transformation to act upon. Hinton and Parsons, however, showed that even in the absence of the letter identity, people could use prior angle knowledge if all of the potential test letters opened to the same side, had a common front and back. A frame with a front and back evidently provides sufficient architecture that the mind can grab onto it and do things with it. Perhaps this same property allows a parallel process in mirror inversion search. People can perform a search based on frame orientation without having to check the contents of the frame.

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