Comparing Perception of Stroop Stimuli in Focused versus Divided Attention Paradigms: Evidence for Dramatic Processing Differences

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Abstract

A huge set of focused attention experiments show that when presented with color words printed in color, observers report the ink color faster if the carrier word is the name of the color rather than the name of an alternative color, the Stroop effect. There is also a large number (although not so numerous as the Stroop task) of so-called "redundant targets studies" that are based on divided attention instructions. These almost always indicate that observers report the presence of a visual target ('redness' in the stimulus) faster if there are two replications of the target (the word RED in red ink color) than if only one is present (RED in green or GREEN in red). The present set of four experiments employs the same stimuli and same participants in both designs. Evidence supports the traditional interference account of the Stroop effect, but also supports a non-interference parallel processing account of the word and the color in the divided attention task. Theorists are challenged to find a unifying model that parsimoniously explains both seemingly contradictory results.

Keywords

Stroop effect; separability; independence; race model; coactivation model

The Stroop effect (Stroop, 1935) is a prime example of the human failure to attend selectively to an individual aspect of the stimulus. When naming the color in which color words are printed, people seem unable to ignore the meaning of the carrier words. To gauge the influence of the task-irrelevant words, the Stroop effect is defined as the difference in color-naming performance between congruent (the word naming its color such as RED in red, with the former signifying the word and the latter the color) and incongruent (word and color conflict, such as RED in green) stimuli. Better performance with congruent than with incongruent stimuli shows

that people paid attention to the task-irrelevant words, thereby compromising exclusive focus on the print colors. The robustness of the pattern and its potential utility for understanding central aspects of human attention and automatic action rendered the Stroop effect the single most popular phenomenon in current cognitive science.[1] Despite its popularity, the effect has proven surprisingly resilient to a final theoretical resolution.

The vast majority, if not all, of Stroop designs employ focused attention: The participants are asked to report the color while ignoring the word. The resulting interference is taken then to indicate that people are unable to selectively attend to the color and block out the word meaning. We wondered what would happen if participants were required to attend simultaneously both to the color and the word. That is, we would run an experiment with the original color-word stimuli but in a divided attention paradigm.

Here is our divided attention paradigm with Stroop stimuli. Consider a small stimulus ensemble that includes all four combinations of the words, RED and GREEN, and the ink colors, red and green. In the traditional Stroop task, the participants are instructed to respond to the ink colors while ignoring the carrier words. In our divided attention task, by contrast, the participants are instructed to respond to 'redness' in the Stroop stimulus, regardless of whether the 'redness' comes in the word (RED), the color (red), or both (RED in red). In order to perform successfully in this target detection task, the participant must attend to the color as well as to the word (i.e., divide attention across components of the Stroop stimulus).

Observe that, from an operational angle, the Stroop task and the divided-attention or detection task differ merely in the way that the four stimuli map onto two response options. In the Stroop task, two stimuli map onto one response (red: 'RED in red,' 'GREEN in red'), and the remaining two onto the other response (green: 'RED in green,' 'GREEN in green'). In the target-detection task, three stimuli map onto one response (yes: 'RED in red,' RED in green,' and 'GREEN in red'), and one onto the other response (no: 'GREEN in green'). We can now consider some implications for Stroop theory.

The key question is the presence (or absence) of color-word interaction in the two paradigms. According to accepted Stroop models (reviewed below), the divided attention task invites color-word interaction more than does the traditional Stroop task. In the standard Stroop task, the participants are directed to focus on one channel (color) and to ignore information in another channel (word). The task itself does not invite interaction if none initially exists. Indeed, it is the putative contrast between the task instruction (to ignore the word) and the Stroop effect (betraying the influence of the task-irrelevant word) that has abetted the tendency in the literature to endow word reading with automatic properties. In the divided attention or detection task, by contrast, the participants are directed to attend to information in both channels. Therefore, the detection task invites interaction or co-activation, and it does so with force given targets as strongly related semantically as are color-words and colors. This architecture is highly probable in the detection task when one also recalls that the instructions to attend to a single channel in the standard task already seem to produce an interaction expressed as the Stroop effect.

Startlingly, the present results appear to be at odds with these straightforward extrapolations of most models and explanations of the standard Stroop task. We did not find the expected interactive architecture using state of the art tools of stochastic modeling. Note though that the extrapolation and contraposition of the two tasks rests on the assumption that the processing

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[1]Despite the availability of electronic search tools, it has proved surprisingly difficult to arrive at a consensual estimate of the number of studies of the Stroop effect published since Stroop's (1935) original research. Based on several independent estimates, our own conservative one puts the number at approximately 2500 reports.

of the color and word attributes is governed by a common architecture. We return to discuss this assumption

In sum, uncovering color-word interaction in the divided attention task would support traditional Stroop theorizing that posits some type of a cross-talk between word and color at the root of the behavioral Stroop effect. This interactive architecture is eminently plausible under the divided attention environment of the detection task. By the same token, uncovering an independent architecture under the same conditions challenges traditional interaction theory.

Brief Summary of Stroop Models and Theoretical Questions

Word-color interaction (often in the form of interference) forms a basic assumption of major theories of the Stroop effect. Word and color could interact at several loci along their separate processing channels and a number of possibilities have been proffered in the literature. However, the simple coactivation model in which color and word information coalesce downstream (Figure 1B) appears to depict a minimally complex mode of processing which permits inhibition or facilitation over and above that afforded by standard parallel processing. While evaluation of the myriad of explanations of the Stroop effect through the present experimental results lies far beyond our scope (and perhaps that of any single study), the following material quickly reviews some of the major approaches.

On the dominant automaticity view, reading the word is said to be fast, ballistic, and obligatory, an activity that does not draw on resources of attention. Naming the color, in contrast, is generally slower, voluntary and effortful, hence an activity that does require attention. Consequently, the Stroop effect arises from people's effort to overcome their automatic tendencies to read the word when attempting to respond to the colors. Modern theories of automatic activation (Cohen, Dunbar, & McClelland, 1990; Logan, 1980; MacLeod & Dunbar, 1988) view automaticity as a continuum (rather than a dichotomy), assert that interaction can occur throughout the course of processing, and allow for parallel continuous accrual of evidence toward decision. In Logan's (1980) theory, evidence accumulates separately for word and color (weighted by degree of automaticity and distractor validity) and a response is executed when the sum of evidence for the appropriate target exceeds a threshold. The three-layer network developed by Cohen et al (1990) works by accruing evidence forward along the word and the color pathways so that the total activation received by the output units (word, color) determines which will first cross its threshold for responding.

Another popular instantiation of word-color complementarity, the relative speed of processing account (MacLeod, 1991), explicitly places the interaction in the final response stage (hence the response competition view; Dyer, 1973; Morton & Chambers, 1973; Posner & Snyder, 1975; Stroop, 1935). On the relative speed of processing account, words are theorized to be processed intrinsically more efficiently than colors. The resulting difference in speed affords words prior entry into a "response channel into which only one of the two potential responses can be admitted at a time" (MacLeod, 1991, p. 188).

Other theories of the Stroop effect (e.g., Phaf, van der Heiden, & Hudson, 1990; Roelofs, 2003; Virzi & Egeth, 1985; Zhang, Zhang, & Kornblum, 1999) share the assumption of color-word interaction at some stage of processing. Typically, the interaction is governed by the automatic dominance of word over color when the two clash within the semantic conflict engendered by the specific makeup of the Stroop (incongruent) stimulus. A notable exception in this respect is the recent theory by Melara and Algom (2003), which minimizes the role of automatic activation and semantic conflict in generating the Stroop effect (see also Lindsay & Jacoby, 1994, for a proposal of independent processing of word and color leading to Stroop effects).

In the Melara and Algom theory, the Stroop effect is mutable, molded through the confluence of contexts. Slight stimulus manipulations (e.g., making the color more salient than the word, reducing the correlation over trials between word and color, presenting more colors than words) suffice to eliminate or to reverse the Stroop effect (Algom, Dekel, & Pansky, 1996; Dishon-Berkovits & Algom, 2000; Melara & Algom, 2003; Melara & Mounts, 1993; Sabri, Melara, & Algom, 2001). This plastic, contextual basis of the Stroop phenomenon is inharmonious with strong automaticity. The advantage of congruent over incongruent stimuli (= the Stroop effect) is explained by the trivial fact that with the former stimuli both attributes presented for view (word and color) count for the correct response, whereas with the latter stimuli only the color does so. The role of semantic clash or agreement thus is minimized to the number of elements in each display counting for or counting against the correct response (with the processing of each element remaining the same in congruent and incongruent preparations).

In view of the limited role of automaticity and semantic factors in generating the Stroop effect (in the approach advanced by Melara and Algom, at the least), it seems only appropriate to ask: Can some form of independent parallel processing predict the traditional Stroop effect in the usual focused attention paradigm? Note that a positive answer to this question would amount to a radical new conception of the effect. Conversely, Will a Stroop-like interaction between word and color appear in the divided attention paradigm? Suppose that the answers to the above two queries are: 1. "No, independent parallel models cannot, in general, predict the Stroop phenomenon in the usual focused attention task." 2. "No, Stroop-like interaction fails to appear in the divided attention paradigm." Then, a striking challenge to Stroop theorists would be laid down: How can theories based on interference in a focused attention task, especially if it is more-or-less automatic, suddenly transform into an independent mode of processing in a divided attention paradigm, the latter seeming to beg for interaction?

Our array of response time (RT) methodologies, "systems factorial technology" (e.g., Townsend, 1972, 1984, Townsend and Ashby, 1983; see Townsend and Nozawa, 1995, for a comprehensive treatment), is well suited to explore fundamental processing characteristics of performance in a divided attention paradigm. Our toolkit is also well suited to assist in comparing the results with those obtained in the typical Stroop paradigm. Because the current design and associated tools are not widely known within the main body of Stroop query, we next describe them in a succinct fashion. We discuss then the pertinent models, predictions, and their implications for Stroop theory. A number of key terms pertinent to the present discussion are quantitatively defined in the Appendix for easy reference.

Model Diagnosis: Systems Factorial Technology

Consider two important types of parallel processing of, say, words and their print colors presented in Figure 1: Neither the word channel nor the color channel waits for the other channel to finish before it starts to process its own input. Assume that detection of either the word target or the color target is sufficient to determine a correct response. Is there a cross-channel interaction in processing? In the race model depicted in Figure 1A the processing is entirely separate: The response is determined completely by whichever channel that wins the race. In the coactivation model depicted in Figure 1B, by contrast, information from the two channels is combined before a decision is made. The two sources of information coalesce downstream to satisfy the criterion for responding. This is an extreme form of parallel channel interaction.

The Redundant Targets Paradigm

How can one decide between the competing models? Our detection task, also known as the redundant targets paradigm, can provide a platform for deciding between race and coactive models (and, as a result, between the associated Stroop theories). Of the set of stimulus attributes, some are defined as targets, the others as distractors. A pair of attributes is presented

on each trial, and the observers respond "yes" when the display contains at least one target attribute; otherwise they respond "no." Referring to our example from the Stroop milieu, the word RED and the print color red ('redness') can be defined then as targets with GREEN and green as distractors. In this setup, the word RED printed in red is a double- or redundant-targets display, and RED in green and GREEN in red are single-target displays. Because at least one target is always present, all of these stimuli require a "yes" response. The display with the word GREEN in green contains only distractors and requires a "no" response. Of course, other definitions of targets, such as the instruction, "say 'yes' if either the word is RED or the color is green" are possible as we will see (and test) below.

The Race Model Inequality: Race versus Coactivation

A valuable mark of performance in the redundant targets paradigm is the redundant targets effect (RTE): Reaction times are stochastically faster on double (i.e., redundant) targets trials than on single-target trials (e.g., Egeth & Dagenbach, 1991; Miller, 1982; Townsend & Honey, 2007; Townsend & Nozawa, 1995). In the example of the detection task, the mean reaction time to RED in red should be faster than to RED in green or to GREEN in red despite the fact that all three displays include a target and that all thus require the "yes" response. The magnitude of the RTE, in turn, reflects on the nature of processing, i.e., whether or not there is an interaction between the word and the color information. On the one hand, the observed speedup on trials with redundant targets (relative to single target-with-distractor trials) is naturally produced by an interaction between the two processing channels. On the other hand, the speedup when both targets are present can occur via statistical considerations alone (Raab, 1962; Townsend & Honey, 2007).[2]

In order to decide between the alternatives, Miller (1982) pointed out that all race models must satisfy the inequality, $F_{WC}(t) \leq F_W(t) + F_C(t)$, where the subscripts W, C, and WC indicate that a target was present on the word channel (RED), the color channel (red), or both (RED in red); F_W, F_C, and F_{WC}, are the respective cumulative distribution functions of the response times for the three classes of trials. The inequality means that the distribution function for trials in which both targets are present cannot exceed the sum of the distribution functions for trials entailing a single target -- if indeed there is a parallel separate race at the basis of the RTE. Alternatively, violation of the race model inequality falsifies all race models, and implies that an interaction or coactivation of the two channels produces the RTE.[3]

In order to test the race model inequality, one has to calculate the cumulative distributions of response times separately for each of the three types of trials: double targets (RED in red), single target RED (i.e., RED in green), and single target red (i.e., GREEN in red). The left-hand panel of Figure 2A illustrates the pattern of distribution functions, F(t), predicted by the separate channels theory. Notice the presence of the RTE: F(RED in red) > [F(RED in green) or F(GREEN in red)] at all time t, implying shorter mean RT to the redundant-targets stimulus than to either of the single-target stimuli. Nevertheless, the <u>empirical</u> function for the redundant targets trials, F(RED in red), does not cross the theoretical function summing the distribution functions for the individual targets presented alone, F(RED in green) + F(GREEN in red). In fact, F(RED in red) < [F(RED in green) + F(GREEN in red)] at all time t. Therefore, the race model inequality is not violated. Contrast this pattern with that predicted by interaction or coactivation theory in the right-hand panel. The distribution functions look similar, hence entail

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[2]The observed speedup in the redundant target condition can simply be the consequence of the fact that for any two random variables (say, W and C, the response times for word and color, respectively), E[min(W, C)] ≤min(E[W], E[C]), from which it follows that we will experimentally observe E[min(RT$_W$, RT$_C$)] ≤min(E[RT$_W$], E[RT$_C$]).

[3]For continuity with many studies in the literature, we comply with the usual convention of "race," which is basically equivalent to Miller's bound. Naturally, two highly interactive channels that produce RTs which violate that bound can nonetheless 'race' in the sense that there may be a distinct activation criterion in each channel. The first moment that either of these channels reaches its criterion evokes a decision and response (see, Colonius & Townsend, 1997; Mordkoff & Yantis, 1991; Townsend & Wenger, 2004).

an appreciable RTE, but now F(RED in red) > [F(RED in green) + F(GREEN in red)] at some time t. The race model inequality is violated: The responses to RED in red are faster than expected on the basis of strictly separate processing of word and color.

Observe that both theories predict an RTE (as indicated in Figure 2A). The key difference between the patterns is the source (and size) of the speedup on redundant targets trials. According to separate channels theory (race architecture), the responses to RED in red are speedy because they are determined by the faster process on any particular trial. According to interaction or coactivation theory, the responses to RED in red are especially fast because information from the word and color targets combines to swiftly satisfy a single decision criterion. As we show when discussing capacity below, the separate channels model is consistent with unlimited capacity meaning that the quality of processing a target in any one channel is not impaired, limited, or enhanced by other ongoing processing. This model is also consistent with the satisfaction of the race model inequality. In contrast, the coactivation model is consistent with super capacity meaning that the quality of processing a target in a given channel improves when other ongoing processing intensifies. And, the race model inequality is always violated under coactivation.[4]

We tested the race model inequality through the respective survivor functions, too (see Townsend & Nozawa, 1995, for derivations and proofs). If F(t) is the distribution function of response times, then the survivor function, S(t), is its complement, $S(t) = 1 - F(t)$. Where F(t) tells us the probability that processing is done at or before time t, S(t) tells us that the process is not done, i.e., that it is finished later than time t. In the survivor version test of the race model inequality, positive values of the expression, $S_{WC}(t) - S_W(t) - S_C(t) - 1$, satisfy the inequality, whereas negative values violate it. In Figure 2B we illustrate the testing of the race inequality through the survivor functions. In the left-hand panel (separate channels theory), the predicted values are all positive, whereas in the right-hand panel (interaction theory), some of the predicted values are negative.

The Capacity Coefficient Diagnostics: Limited-, Unlimited-, and Super-Capacity

It is now generally recognized that the race model inequality reflects directly on the capacity of the system (cf. Ashby & Townsend, 1986; Colonius, 1990; Luce, 1986). A recent mathematical theory includes the race model bound as well as the Grice bound (see below) in a general theory of capacity (Townsend & Nozawa, 1995; Townsend & Wenger, 2004). Again, unlimited capacity means that processing efficiency in any given channel neither degrades nor improves as other channels (i.e., targets) are brought into play. The processing (reaction time) of a given target remains invariant whether or not another target is simultaneously presented. We often call this the "standard parallel model." Limited capacity means that a given channel slows down as the number of active channels (i.e., those carrying targets) increases, relative to what is expected from the standard parallel model. Super capacity means that channel activity is more efficient (i.e., faster) as the number of active channels increases. A statistic we refer to as the capacity coefficient, C(t), gauges the extent to which target processing in one channel is impaired [C(t) < 1, limited capacity], unaffected [C(t) = 1, unlimited capacity], or improved [C(t) > 1, super capacity] by adding a target in the other channel (Townsend & Nozawa, 1995; Townsend & Wenger, 2004). Formally, the capacity coefficient, C(t), is defined as

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[4]If the original parallel channels do not interact before summing and are by themselves, unlimited capacity (that is, up until summation the parallel channels are processing just as they would in a separate decisions, non-interactive system; Townsend & Nozawa, 1995).

$$C(t) = \frac{H_{WC}(t)}{H_W(t) + H_C(t)} \quad t > 0,$$

where $H_W(t)$, $H_C(t)$, and $H_{WC}(t)$ are the integrated hazard functions calculated on single- and double-target trials, respectively.[5] Put in a qualitative way, the C(t) is a fine-grained, dynamic index of the efficiency of processing accomplished with respect to a given target/channel (i.e., it eschews the static notion of capacity as some kind of a storehouse).[6]

The calculation of C(t) is simple. Recall that the hazard function, h(t), and hence the integrated hazard function, H(t), is a function of S(t), the survivor function. S(t), one recalls, is simply the complement of F(t), the distribution function of the observed RTs. Using the identity from probability theory, $H(t) = -\log[S(t)]$, makes it possible to estimate the integrated hazard function and consequently C(t) directly from the empirical survivor function [Wenger & Townsend (2000) provide a highly accessible guide of the steps needed to be taken in order to calculate H(t) and associated measures]. We calculated the C(t) measure in our experiments in order to assess capacity in moving from single to double targets.

Figure 2D presents the contrasting predictions by the parallel race and the coactivation models concerning the capacity coefficient C(t). In the left-hand panel, the values hover at around unity, reflecting the prediction of separate channels theory that the system is unlimited capacity. In the right-hand panel, by contrast, the values exceed unity and signify super capacity as should be the case if the word and color targets interact in processing.

The Grice Bound

The race model inequality can be considered, as seen above, as an upper bound on capacity (in parallel race models). There is also a lower bound on limited capacity, mentioned above, the Grice inequality (Grice, Canham, & Gwynne, 1984). Violation of this bound means that the system is very sensitive to any increase in load even if the added load entails the sought target. Thus, adding a second channel entailing the target of the first -- thereby rendering the situation that of redundant targets -- impairs performance instead of enhancing it (as in a system of greater capacity). Formally, violation of the inequality, $MAX[F_W(t), F_C(t)] \leq F_{WC}(t)$, means that the system is of limited capacity to a rather strong degree. In this case, performance on double-target trials [$F_{WC}(t)$] is <u>slower</u> than that on single-target trials containing the faster of the two targets, $MAX[F_W(t), F_C(t)]$. In order to test the Grice bound, we again used the survivor function version in which negative values of the expression, $MIN[S_W(t), S_C(t)] - S_{WC}(t)$, imply capacity limitations more severe than those imposed by the Grice bound. Such violations indicate efficiency drops with increased workload.[7]

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[5]The hazard function, h(t) = f(t)/S(t) gives the probability that the processing of an item finishes in the next instant given that it has not finished yet. The integrated hazard function, H(t), is defined as the integral of the hazard function from zero to time t.

[6]We recounted earlier the generic relationship between capacity and the race model inequality, but some qualifications are in order by way of a more rigorous statement. Thus, super capacity may be sufficiently modest that the race model inequality is not violated, although super capacity very early in processing does imply violation (Townsend & Nozawa, 1995). On the other hand, violations of the race model bound do imply super capacity; the violations can be of a rather substantial degree if coming late in processing. Consistent with our general point, coactivation parallel models can predict striking super capacity (Townsend & Wenger, 2004). Of course, this assumes that when both channels are active as opposed to one, there is no influence that slows both down, such as strong lateral inhibition. Our simulations indicate that extreme interference would be required to give coactivation an appearance of limited capacity (Townsend & Wenger, 2004). Nevertheless, a strong coactivation-produced interaction could also precipitate interference, if one channel subtracts while the other adds, in the overall pooling of activation. Hence, in this investigation, we generalize the usual notion of coactivation to include the possibility of interference and consequent limited capacity, as opposed to the usual confinement of coactivation to "better than a race" types of facilitation.

[7]That are typically as bad as or worse than ordinary serial processing.

Figure 2C offers the survivor form predictions with respect to the Grice bound. Neither race nor coactivation theory predicts severe limitations on capacity, so few violations of the bound are expected (i.e., virtually all values are expected to be positive). Nevertheless, a limited number of violations in real data may not be incommensurate with a separate channel theory (due to baseline responding, cf. Townsend & Honey, 2007).

The Subset of Double Targets Trials: Direct Evidence for Architecture

Our final tool was based on an extension of the standard redundant target paradigm. This extension enables one to gather stronger corroborating evidence on architecture. The standard redundant targets experiment recounted entails a simple 2×2 factorial design: Each of the two main factors (Word, Color) is binary valued as target and distractor. However, one can create another factorial design confined solely to the double-target stimulus, RED in red. Varying the salience (high, low) of each of its two components creates the following four stimulus combinations: highly legible RED printed in highly salient red (h, h), highly legible RED in low-saliency red (h, l), low-legibility RED in highly salient red (l, h), and low-legibility RED in low-saliency red (l, l). Consider the possible outcomes for this factorial design through the respective factorial plots of Figure 3 The factorial plot may entail parallel lines (thereby exhibiting an additive structure) or converging or diverging lines (thereby exhibiting interaction). Notice that each line in the factorial plot is determined by the difference between its two end-points. Now the difference of these two differences is called the mean interaction contrast (MIC), and it provides a convenient statistic to summarize the presence, size, and direction of the interaction in a given factorial plot. Thus,

$$MIC = RT(l, l) - RT(h, l) - RT(l, h) + RT(h, h).$$

Clearly, MIC is zero for an additive structure; otherwise there is an interaction. When MIC is negative, the interaction is termed under additive; when MIC is positive the interaction is over additive.

In a parallel race, the responses will be speedy on all but the (l, l) trials due to the fast processing of the good quality attribute of either target. Consequently, an over additive interaction is expected. Notably, the same interaction is expected for the coactivation model.[8] Clearly, the MIC predictions are not diagnostic to decide between a race and a coactivation model. However, the following extension is.

Within the factorial design entailing the double-target stimulus, each of the four combinations, (l, l), (l, h), (h, l), and (h, h), is presented many times, of course, so that each has its own RT distribution. Slice these four RT distributions into small time bins (of, say, 10-ms each, so that the bins cover the entire range of RT; for an RT range between 200 and 800 ms, the bins would be 200–209 ms, 210–219 ms….. 790–799 ms, using rounding). Evaluate the distributions at each time bin t to generate the four values needed to create the factorial plot at <u>that</u> t. Doing so with respect to the pertinent survivor functions (replacing the respective means without much consequence except for mathematical convenience) gives the survivor interaction contrast, SIC (t). Townsend and Nozawa (1995) proved that the SIC(t) function does provide the sought dissociation of predictions.[9] For parallel race, the SIC(t) function is positive throughout the

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[8]Of course, these assertions have been rigorously proven (for MIC predictions see Schweickert & Townsend, 1989; Townsend & Ashby, 1983). Note also that the predictions apply with a minimum time stopping rule. The stopping rule defines the moment at which the system terminates processing. Within a redundant target search task, a minimum-time stopping rule means that processing terminates as soon as a single target is detected. With an exhaustive stopping rule, on the other hand, processing information from all incoming sources (channels) has to be completed before a decision is made.

[9]The proof incorporates the critical assumption of selective influence (Dzhafarov, 1997; Townsend & Schweickert, 1989).

entire range of t. For coactivation, the function is negative early on, but this trend is counteracted later by much more dominant positive values. We computed the MIC and the SIC(t) functions for our data.

The present double factorial paradigm (one paradigm for the standard redundant targets design, the other for the subset of double targets trials) permitted for a division of labor in recovering key features of the model that governs the processing of Stroop color-word stimuli.

The predictions concerning this factorial design with exclusively redundant-targets (RED and red in high and low quality) are illustrated in Figure 4. Both separate channel and interaction theory predict an over additive interaction at the level of the means (Figure 4A; see Figure 3 again). However, as shown in Figure 4B, this pattern is produced by an SIC(t) function that is always positive if processing is separate (left-hand panel), but by an SIC(t) function that is at first negative and then turns overwhelmingly positive if processing is coactive (right-hand panel).

The Present Study

With this brief survey of the landscape of systems factorial technology along with the associated diagnostic predictions, one is in a better position to appreciate the theoretical potential of the present comparison between focused and divided attention tasks with Stroop stimuli. The following 4 experiments entailed two separate tasks each. The participant performed in the standard Stroop task (classifying print colors) and in the redundant targets task (detecting the presence of targets). Notably, the same stimuli served in both tasks: The color words RED and GREEN printed each in red and green were presented. In both tasks, a single color word in color was presented on a trial. The tasks differed in the allocation of two responses onto four stimulus attributes.

In the Stroop task, the participants classified the print colors, giving one response (R1) to the color red and another response (R2) to the color green. In the redundant targets task, the participants detected the presence or absence of at least one target attribute. They gave one response (R1) if at least one target was present, and another response (R2) if none of the target attributes was present. Table 1 illustrates the different assignment of the same stimulus attributes to the two possible responses in the Stroop task and in the detection tasks (with RED and red defined as the targets). The Stroop effect is the difference in color classification performance between congruent (the word naming its print color) and incongruent (word and color conflict) stimuli (given by the mean difference between the two diagonals in Table 1). To illustrate a target detection measure, the RTE is the difference between the responses to RED in red (redundant targets) and those to the RED in green and GREEN in red (single targets; given by the difference between the upper left cell and the major diagonal in Table 1).

In the detection task, we varied the definition of the target attributes across the experiments. They were RED and red in Experiments 1, 2, and for half of the participants in Experiment 4, but were RED and green in Experiment 3 and for the other half of the participants in Experiment 4. Consequently, the double target stimulus was a Stroop congruent stimulus in some of the experiments (RED in red), but was a Stroop incongruent stimulus in the other experiments (RED in green).

Participants responded manually by pressing one of two keys. This is a standard procedure used in the literature with both tasks. For the Stroop task in particular, although oral responding was used in earlier studies, the majority of modern Stroop studies employ manual responses that reliably produce the effect (see MacLeod, 1991, and Melara & Algom, 2003, for reviews).

Finally, we also manipulated the perceptual quality of the stimulus attributes. The words and the colors each appeared in good or bad quality. This manipulation enabled the second factorial design, erected for the cell with the redundant targets (i.e., displays in which both the word and the color are valued as targets). As we recounted, the double factorial paradigm supported model diagnosis and validation.

Experiment 1

Method

Participants—Twelve undergraduate students from Tel-Aviv University performed in a color-classification task and in a target search task in two sessions. They performed in partial fulfillment of course requirements. All had normal or corrected to normal vision and intact color vision. Their ages ranged between 20 and 25 years. A random half first performed in the color-classification task and the remaining half first performed in the target detection task.

Stimuli and Apparatus—The stimulus set comprised all 16 combinations of (the Hebrew words for) RED and GREEN in highly legible and in less highly legible font and the red and green colors in good and bad quality. The stimuli were generated via Microsoft Painter by an IBM compatible (PC-486) microcomputer and displayed on a super-VGA 14-inch color monitor. On a trial, a single color word printed in color appeared in the center over the gray background of the screen. To avoid adaptation and responding strategies based on conscious avoidance of the word, we introduced a trial-to-trial spatial uncertainty of up to 40 pixels around the target location. The viewing distance was approximately 50 cm from the center of the screen such that stimuli subtended a visual angle of 3.66 and 1.146 deg in length and width, respectively.

Based on extensive pilot testing with the Stroop task, we shaped the fonts and determined the colors such that the speed and accuracy of the classifications along the constituent dimensions of word and color would roughly match. Indeed, the mean RTs for word and for color classification obtained for an independent group of 24 young men and women on a shortened version of the Stroop task (48 trials each for reading and for color naming) did not differ appreciably. They were 406 and 412 ms, respectively, for reading and naming (F < 1, errors were negligibly low in both tasks). For word, the high-quality stimuli were generated in Hebrew font Miriam; degrading this standard font by introducing slight changes into the shape of each character yielded the low-quality font. For color, good-quality red had values of 0, 200, and 120, respectively, for hue, saturation, and luminance on the 0–255 point scales of Microsoft Painter. The respective values of 0, 150, and 160 defined red in lesser quality. Good-quality green was defined by 80, 240, and 85 units, whereas the lesser green was produced by values of 80, 150, and 150. We used the resulting set of 16 stimuli in the following two tasks.

The Stroop Task: A single word in color appeared on a trial. The participant classified, while timed, the print color of the stimulus in 8 training trials (unbeknownst to the participant and excluded from the analysis), followed by 64 experimental trials, with the task-irrelevant word varying in an orthogonal fashion (i.e., words and colors were not correlated over the trials). Trials were presented in a random order, subject to the proviso that no more than 3 stimuli with the same correct response appeared in sequence.

The Target Search Task: Again, a single word in color appeared on a trial. And, again, the responses were timed. The target was defined as "redness" in the stimulus. The participant made a "yes" response when she or he detected the word RED, the print color red or both, and made a "no" response when none of these were present (i.e., GREEN in green appeared). Presentation order was random. The participant performed in 3 blocks of 400 trials each, the first 16 of which always serving as practice. The number of trials used in the detection and

Stroop tasks in this and in the subsequent experiments reflect accepted practice; application of the methods of systems factorial technology demands large numbers of observations (Wenger & Townsend, 2000).

Procedure—The participants were tested individually in a dimly lit room. Each performed in the Stroop task and in the Target Search task. Responses in both tasks were made by pressing either a right- or a left-hand key on the keyboard. The participants were encouraged to respond as quickly and accurately as possible. In the Stroop task, the participant pressed one key if the print color was red and another key if the print color was green. In the target search task, the participant pressed one key if one or both targets were present and another key if none were present. In each task, key assignment was counterbalanced. In the Stroop task, one key was assigned for "red" for some participants, whereas the same key was assigned for "green" for the other participants. In the target search task, half of the participants responded affirmatively with the right-hand key, and half responded affirmatively with the left-hand key. Stimulus exposure was response terminated in both tasks. In each trial, the stimulus was presented following a 500 ms pause after the previous response was given.

Data Analysis—Accuracy levels for all observers in this and the following experiments were above 95% in the Stroop task, and above 94% in the target detection task. In none of the experiments did we find a dependable RT-error tradeoff or an interaction with hand. Analyses of the RT data were restricted to correct responses in both tasks. Because the primary interest in the present study was patterns of RT, we do not refer to accuracy in our discussions.

Results and Discussion

The Stroop Task—In the Stroop task, the means were 355 and 366 ms, respectively, for congruent and incongruent stimuli. Their difference amounted to a small but reliable Stroop effect of 11 ms [$t(11) = 4.2$, $p < .01$]. Our participants classified the print color of a conflicting color word a bit slower than they did that of a congruent color. Gauged by the Stroop effect, selective attention to color was compromised albeit to a rather small degree.[10]

The Detection Task—The mean RTs were 467, 359, and 320 ms, respectively, for the target-absent, faster single-target, and redundant-targets displays [$t(11) = 5.7$, $p < .001$, for the latter contrast], thereby documenting the presence of a healthy RTE. Which model does the observed RTE support? To answer the question, we examined whether the data did or did not violate the race model inequality. The massive concentration of positive values in the survivor form test of Figure 5A argues against super capacity. The results show that an RTE occurs for double targets, but that this gain does not derive from the integration of the target attributes or from a particularly efficient processing of these redundant attributes (i.e., of RED in red).

We tested the Grice bound to gain more information, again using the survivor functions (Figure 5B). The area of interest lies below zero because values in that region imply capacity limitations more severe then that imposed by the bound, MIN (S [W (t)], S [C (t)]). Observe that none of the experimental values is negative. Grice's inequality is not violated, implying that capacity was not severely limited in Experiment 1.

The results with respect to the two bounds suggest that the system is neither (severely) limited capacity nor strongly super capacity. They suggest that the observed RTE reflects statistical

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[10]These results are also notable for showing that, when care is taken to match the salience of the presented words and colors, the Stroop effect can be reduced or eliminated (cf. Melara & Algom, 2003; Pansky & Algom, 1999, 2002; Sabri, Melara, & Algom, 2001). The malleability of the Stroop effect and its dependence on context is not easily reconciled with positions of strong automaticity or with the widespread belief that the effect is robust and inevitable (cf. Besner, 2001; Dishon-Berkovits & Algom, 2000; Lindsay & Jacoby, 1994; Monahan, 2001; Stolz & Besner, 1999).

facilitation with separately processed word and color signals. In Figure 5C, we present decisive evidence on capacity. The results with respect to the C(t) measure support unlimited capacity (and reject super capacity) because the data points are very close to 1 for all values of t. When presenting RED in red for view, the individual processing capacity in the word channel and in the color channel is exactly as good as it is when these respective targets are presented singly for view (i.e., in RED in green or GREEN in red). In other words, adding a harmonious (redundant) target attribute did not affect the processing of the word RED or of the color red.

We had planned to examine the factorial design based on the subset of redundant trials. Unfortunately, our manipulation of stimulus salience was not successful and our degraded stimuli did not yield appreciably longer RTs than did the intact stimuli (an extra 6 ms for word and an extra 4 ms for color on average for the degraded attributes). Consequently, the analyses of Experiment 1 rest on the results of the standard redundant target design.

In summary, the capacity coefficient, C(t), and the two inequalities converge on the conclusion that the system is unlimited capacity. Unlimited capacity in processing of Stroop stimuli is a striking result. After all, super capacity is the natural mode of processing for attributes as strongly bonded semantically as are RED and red. Yet super capacity was absent from the present data. Despite the semantic congruity, the components of RED in red were processed as efficiently, not more efficiently, and apparently in a parallel mode, as when they were appearing in the incongruent combinations. The present results suggest a minimum time horse race along separate channels for the processing of Stroop color-word stimuli. This structure is inconsistent with coactivation or other interactive-channels models. To adduce further evidence for the present quite startling conclusion, in Experiment 2 we made a concerted effort to apply the double factorial design in full.

Experiment 2

Method

Participants—Five Tel-Aviv University undergraduates were paid to participate in the experiment. They had normal or corrected to normal vision and intact color vision. Their ages ranged between 21 and 28 years. The participants performed in 5 experimental sessions of approximately 1.5 h each, separated from one another by at least a day.

Stimuli and Apparatus—The apparatus was that of Experiment 1. The high quality stimuli were those used in Experiment 1. However, we changed the values for the degraded attributes. In the case of words, we introduced larger changes into the characters of the standard Miriam font than those applied in Experiment 1 (yet each word was still legible with virtually errorless performance). For color, we changed the values for red to 0, 70, and 215, respectively, for hue, saturation, and brightness on the scales of Experiment 1. For degraded green, the corresponding values were 80, 30, and 210.

To enable an extensive examination of the data of each of the individual participants, we enhanced statistical power by substantially increasing the number of trials in each task. We increased fourfold the number of trials in the Stroop task, so that this task included 256 trials in this experiment. We similarly increased the number of trials in the target detection task, so that each participant performed in 16 blocks of 400 trials each. Prior to these experimental blocks, the participant performed in a block of 400 trials as practice. Therefore, the participant in Experiment 2 performed in a total of 6800 trials in the detection task.

Procedure—The procedure followed that of Experiment 1. Participants 1, 2, and 5 first performed in the Stroop task and participants 3 and 4 first performed in the target search task. Key assignment was partially counterbalanced as in Experiment 1. To minimize the influence

of one task upon the other, the Stroop and the detection tasks were performed in different days (as were the consecutive sessions of the detection task itself).

Results and Discussion

The Stroop Effect—The overall means were 393 and 410 ms, respectively, for congruent and incongruent stimuli, yielding a Stroop effect of 17 ms in the pooled data [$t(4) = 3.8$, $p < .01$]. The individual performers varied considerably. The data of two participants (participants 3 and 5) exhibited appreciable Stroop effects [30 and 32 ms, respectively; $t(114) = 2.4$ and $t(121) = 2.5$, $p < .01$], whereas those of the other participants did not. The latter had non-significant effects of 6, 7, and 8 ms, respectively.

The Detection Task—The mean RTs were 568, 423, and 380 ms, respectively, for target-absent, faster single-target, and redundant-targets trials [$t(4) = 9.1$, $p < .001$, for the last contrast], documenting the presence of an RTE. In order to tap its source, in Figure 6A we examined the race model inequality. In Figure 6B we examined the Grice bound. The exclusively positive values in each panel show that neither inequality was violated. The results in Figure 6A argue against coactivation and super capacity. The participants reaped a gain from exposure to the redundant target attributes in the RED in red stimulus, yet the gain did not result from coactivation of the two attributes or super capacity in their processing. The results in Figure 6B, satisfying the Grice bound, argue against limited capacity to any severe degree.

In Figure 7, we estimated $C(t)$. The data (pooled and individual) appear to support a small degree of limited capacity as many values hover just below 1. The individual channels for color and word seem to be suffering a very slight degradation when moving from one target attribute to two attributes. It is also plausible that the data reflect the potential contribution of base time, mildly lowering the estimates of capacity (Townsend & Honey, 2007). Be that as it may, the $C(t)$ measure clearly shows that capacity was not super in the system processing components of Stroop stimuli. Collectively, the results suggest a parallel race. In order to cross-validate this conclusion, we next examined the subset of data from the redundant targets trials -- the second leg of the double factorial design.

Shown in Figure 8A is the factorial plot of target attribute (RED, red) by salience (good, bad). The interaction was reliable for the group data [$F(1,4) = 84.1$, $p < .001$], and it was similarly reliable for each of the five participants [for the individual sets of data, $F(1, 386) \geq 14.7$, $p \leq .001$]. A critical feature to examine is the form of these interactions. Clearly, the mean interaction contrast in Figure 8A is positive, evincing an over additive interaction. An over additive pattern supports (minimum time) parallel processing, but it does not distinguish between race and coactivation. To decide between the two models, we reproduced the factorial plot of Figure 8A at each point of time (in bins of 10 ms) and calculated the pertinent survivor interaction contrast, $SIC(t)$. Recall the different predictions: coactivation: $SIC(t) < 0$ for small t but $SIC(t) > 0$ for larger values of t; parallel race: $SIC(t) > 0$ at all time t. The survivor interaction contrasts in Figure 8B are overwhelmingly positive, a pattern consistent with processing along separate channels. The massive positive concentration was found for four of the five observers. The evidence for a parallel race is strong as is the counterevidence against coactivation.

In Figure 9, we present the mean factorial plots and the associated $SIC(t)$ functions for the two observers who exhibited statistically significant Stroop effects in the selective attention task. The mean factorial plot and the $SIC(t)$ functions are positive for both observers, supporting parallel processing. However, as is evident in Figure 10, indications for coactive processing are present in the data of Participant 5 [$C(t) > 1$ for some points and the race model inequality is violated]. This single exception to the pervasive separate processing uncovered in this study might tap the presence of a modicum of individual differences in the underlying architecture.

Nevertheless, a separate mode of processing in tandem with a Stroop effect in color classification is the standard pattern of the current data (see Experiment 4 for further evidence on this point). The data of participant 3 (not presented), by contrast, were fully consistent with those of the majority of the participants and with the group data; there were no violations of the race model inequality and the C(t) values were equal to or smaller than 1.

We conclude with two tests to provide additional validation support. Consider the subset of target-absent trials (GREEN in green) in Figure 11. Recall that these trials yielded the longest RTs despite the fact that the two distractors created a Stroop-congruent stimulus. It is evident in Figure 11A that the mean factorial plot is additive (F < 1) and that the associated SIC(t) function is negative for small values of t, turning positive for larger values of t. Observe in Figure 11B that the amount of negative area is approximately equal to the amount of positive area (unlike coactivation in which the latter is much larger than the former), thereby supporting the additive pattern observed in the mean plot of Figure 11A. This evidence strongly favors serial processing of the distractor-only stimuli in conjunction with an exhaustive stopping rule (e.g., Townsend & Nozawa, 1995). This mode of processing is reasonable, given the change in the required response for these stimuli ("No;" note that the response is "Yes" for all other stimuli)

Experiment 3

In Experiments 1–2, the target attributes were defined as RED and red. Their simultaneous (hence redundant) presentation created a Stroop-congruent stimulus. Despite the congruity, the observed performance was neither super capacity nor coactive (the single exception notwithstanding). In Experiment 3, we changed the definition of the target attributes. The new targets were RED and green; consequently, RED in red and GREEN in green formed the single-target stimuli, and the remaining GREEN in red was the target-absent stimulus. Under this regimen, single-target stimuli created Stroop-congruent combinations, whereas the double-target and the double-distractor stimuli created Stroop-incongruent combinations. This reshuffle provides a strong test for the role of semantic relations in processing. They play a major role in an interactive model, but do not play a role in a race model, which assumes separate (parallel) processing of word and color.

Method

Participants—Four Tel-Aviv University undergraduates were paid to perform in the experiment. Method and criteria of selection as well as the number of experimental sessions were the same as in Experiment 2.

Stimuli and Apparatus—The stimuli were those of Experiment 2. However, the allocation of the colors and words onto targets and distractors differed. The participants were instructed to give an affirmative response to the appearance of the word RED, the color green, or both. They were instructed to give a negative response if none of the target attributes was present (i.e., to the stimulus GREEN in red). All the other details of the method were the same as those used in Experiment 2.

Procedure—The procedure closely followed that of Experiment 2.

Results and Discussion

The Stroop Task—Average color classification performance was 404 ms, with a Stroop effect of 11 ms [t(3) = 3.1, p < .05]. For the individual participants, the effects were 12, −5, −2, and 39 ms, with only the last value statistically reliable [t(118) = 2.6, p < .05]. Taken as a whole, selective attention was compromised, but to a modest extent.

The Detection Task—The mean RTs were 534, 437, and 389 ms, respectively for the target-absent, faster single-target, and the redundant targets trials [$t(3) = 14.4$, $p < .01$ for the last contrast]. The presence of the RTE in these data is remarkable. Recall the makeup of the stimuli: The single-target displays were Stroop-congruent stimuli (with the word naming its print color) whereas the double-target displays were incongruent stimuli (with the word and color conflicting). Nevertheless, an appreciable RTE was obtained with faster responses to Stroop-incongruent stimuli than to Stroop-congruent stimuli.

Whence the RTE? In order to tap its source, in Figure 12A we examined the race model inequality. Clearly, the inequality was not violated, implying the absence of any sizeable super capacity and, hence, a parallel race architecture. The Grice bound (Figure 12B) also was not violated, implying the operation of a system that was not severely limited capacity. The evidence thus supports a parallel system of (approximately) unlimited capacity. The corollary is that the observed RTE derived from the statistical advantage afforded by the presence of multiple target attributes, not from common processing of the color and the word.

The results with respect to the more fine-grained measure of the capacity coefficient, $C(t)$, support unlimited or quite mildly limited capacity. Virtually all the data are located between the values of 0.5 and 1, so that the system was neither super capacity nor severely limited capacity (as might have been the case had the Stroop incompatible target attributes taken a toll on performance). The data depicted in Figures 12A, 12B, and 12C also characterized the data of each of the individual participants, including the one who exhibited an appreciable Stroop effect. The various measures thus coalesce into tapping a parallel system with mildly limited capacity.

Consider now the results with respect to the subset of redundant-targets. Examination of the mean factorial plot (Figure 13A) reveals an interaction [$F(1, 3) = 61.7$, $p < .01$] whose form is positive. The over additive pattern supports the presence of a parallel model with a minimum time stopping rule. Unfolding this contrast in time, i.e., deriving the SIC(t) functions (Figure 13B), reveals an overwhelmingly positive distribution of values at all time t. This pattern supports separate processing along parallel race. The data of each of the individual participants were duplicates of the pooled data [$F(1, 386) \geq 17.1$, $p \leq .05$], displaying over additive patterns at both the mean- and the survivor-contrast levels].

Finally, we examined the results with respect to the subset of target-absent trials. The mean factorial plot (Figure 14A) revealed a negative MIC [$F(1,3) = 6.9$, $p < .01$]. The under additive pattern observed for the means was associated with an SIC(t) function (Figure 14B) that was negative for all values of t. These results argue for parallel processing of the distractors governed by an exhaustive stopping rule (cf, Townsend & Nozawa, 1995). An exhaustive rule is the defining property of the system when processing the target-absent displays (because all distractors must be examined in order to make the correct negation response). This exhaustive examination is sometimes based on a serial (Experiment 2) and sometimes on a parallel (Experiment 3) mode of processing. We do not have a ready explanation for the difference in architecture (although not in stopping rule) across this and the previous experiment.

In summary, the results of Experiment 3 replicated those of Experiment 2 despite the replacement of the targets (and the distractors) in a semantically consequential way. In the face of a wholesale reversal of roles, the underlying model remained invariant. The Stroop-status of the attributes, congruent or incongruent, mattered little to mode of processing. This remarkable outcome validates the race architecture, one that does not afford a role to semantic relations.

Experiment 4

In Experiments 1–3, we selected the colors and the words such that the pair of values along each dimension was salient or discriminable to roughly the same extent. Telling RED and GREEN apart was approximately as difficult (or easy) as telling red and green apart. Under this regimen, we recorded fairly small Stroop effects at the group level, and the effect was sometimes absent at the individual level. The small Stroop effects obtained pose a potential threat to the generality of the conclusions reached in the present study. Experiment 4 was performed in order to address this concern.

In Experiments 1–3, we uncovered an invariant architecture of separate color-word processing in detection in the face of varying amounts of the Stroop effect in classification. Again, the generality of this outcome might be constrained by the fairly small Stroop effects obtained. In order to generate consistently larger Stroop effects, in Experiment 4 we did not attempt to match the salience of the constituent dimensions. The words were presented in a standard font and were printed in prototypical, moderately saturated colors -- the typical preparation used in the vast majority of Stroop experiments (in this preparation, the words are more discriminable than the colors wherefore they intrude on color more than vice versa; cf. Melara & Algom, 2003). Consequently, we expected to record large amounts of the Stroop effect in the data of Experiment 4. Does a race architecture remain in force in the environment of Experiment 4?

A further goal of Experiment 4 was to test once again the effect of the composition of targets on the form of the underlying model. For half of the participants, the target attributes of word and color combined to form a Stroop congruent stimulus (RED and red); for the other half, the word and the color signals formed an incongruent stimulus (RED and green). Does the semantic relationship bonding the target attributes affect detection?

Method

Participants—The participants were 22 Indiana University undergraduates who performed against course credit. All had normal or corrected to normal vision.

Stimuli—The stimulus set consisted of the words RED and GREEN in standard Arial font (size 24 -- chosen to match the length and width of the stimuli used in Experiments 1–3), each printed in red and green. The red color had values of 0, 200, and 120 for hue, saturation, and luminance; the respective values for green were 60, 100, and 200. The stimuli were generated via Microsoft Painter and presented on a Dell 15 computer screen with a resolution of 1024×768 pixels. Stimulus presentation and response recording were controlled by an IBM compatible (Pentium 3) personal computer running DMDX software. All the other details of the presentation and event sequence were the same as in Experiments 1–3.

Design and Procedure—The design and the procedure were the same as in Experiments 1–3 with two notable exceptions. First, the definition of target attributes in the detection task differed across random halves of the participants. Each participant performed in the Stroop task (classifying colors) and in the redundant targets task (detecting target attributes). However, the target attributes were RED and red for 10 of the participants, but RED and green for the remaining 12 participants. Second, we did not manipulate stimulus salience in Experiment 4. Consequently, the double factorial paradigm was not applied. The experiment included the basic factorial design of the redundant targets paradigm with Word (target, distractor) and Color (target, distractor) as the main factors.

Because one participant (#18) had an error rate of 31% in the Stroop task, this set of data was excluded from the results (given the large number of participants, including this subset does not change the pattern of group results).

Results and Discussion

The Stroop Task—For the data pooled over the participants, there was a large Stroop effect of 32.9 ms [$t(20) = 6.1$, $p < .001$]. The Stroop effect for error amounted to 1.2% [$t(20) = 2.4$, $p < .05$]. Notably, large Stroop effects were obtained with virtually all of the individual performers. These results demonstrate the power of context -- of mismatched baseline discriminability in this case -- to shape the ensuing Stroop effect (cf. Melara & Algom, 2003). Most important, we are now in a position to characterize the processing system of individuals who exhibited reliably large Stroop effects.

The Detection Task—The mean RTs for the group observers with RED and red as targets were 530, 456, and 410 ms, respectively, for target-absent, faster single-target, and redundant-targets trials. The RTE of 46 ms was reliable [$t(9) = 4.5$, $p < .001$]. To examine the source of the RTE, we tested the compliance of the data with the race model inequality. As is evident in Figure 15 (left column), the data did not violate the inequality. The Grice inequality (Figure 15, middle column) also was not violated. The capacity coefficients (Figure 15, right column) again hover between 0.5 and unity, arguing against super (or extremely limited) capacity. To enhance validity, we performed the same tests for the data of 4 individual performers with very large Stroop effects. None of these data sets violated the race model inequality (except for a slight violation with those of Participant 6 at a single time [$t = 290$ ms], probably a statistical artifact), the Grice inequality, or exhibited greater than 1 values of capacity. These results are important for two reasons. First, the race architecture is shown to be in force for observers with very large Stroop effects. Second, the present targets formed a Stroop-congruent combination, yet this feature did not engender super capacity in detection. This last result bolsters the validity of the underlying independent parallel race architecture.

The mean RTs for the group with RED and green as targets were 484, 424, and 394 ms, respectively, for target-absent, faster single-target, and redundant-targets trials. The RTE of 30 ms was reliable [$t(10) = 15.7$, $p < .001$]. As is shown in Figure 16, there were no violations of the race model inequality or of the Grice inequality. Values of the capacity coefficient were between 0.5 and 1, arguing against very limited- or super-capacity. We further present in Figure 16 the results of the same tests carried out on the data of 4 individuals with large and statistically significant Stroop effects. The single departure from the group data was recorded by those of participant 17 for some very slight violations of the Grice bound at fast RTs.

Therefore, the results of Experiment 4 dramatically reinforce those of Experiments 1–3. They demonstrate the presence of a standard race architecture for color and word in tandem with reliably large Stroop effects with the same stimuli. The color and word attributes are processed in a separate fashion, yet the classification of color is faster with certain (congruent) values of word. A particularly notable feature of the data was the insensitivity of detection to the definition of targets. The congruent targets RED and red did not engender super capacity. Each target was processed as well -- not better -- when it was the single target present than when it was presented along with its congruent signal. In a complementary fashion, the "conflicting" targets RED and green did not exact any discernible toll on performance. All facets of detection were indifferent to the semantic composition of the redundant targets as they should be, if indeed the architecture is that of separate race.

General Discussion

The Stroop phenomenon is endowed with an uncanny power to trap its investigator. It entails one of the most compelling of human Gestalts, RED in red, presented against an equally compelling visual paradox, RED in green. The observer responds in kind: Performance with the ink color is better with the first stimulus than with the second stimulus (the difference defines the Stroop effect). Given this behavioral outcome, succumbing to a Stroop theory of a

processing conflict between the color and word information seems irresistible. This is a trap, nonetheless, because, from a <u>logical</u> point of view, the presence of Stroop stimuli, on the one hand, and of the Stroop effect, on the other hand, does not mandate a processing conflict. Given (a) a conflict (or agreement) residing in the stimuli and (b) its behavioral expression known as the Stroop effect, the inference (c) that a processing conflict enfolds on the psychological theatre of action seems so natural and innocuous as to render a justification gratuitous. However, (c) does <u>not</u> strictly follow from (a) and (b). The Stroop effect can ensue from completely unrelated psychological processes that do not entail a conflict mirroring that inherent in the stimulus (cf. Garner, 1974). The mental structure can be different from the stimulus structure. More recently, Uttal (2001) underscored this same point: A systems macroscopic or holistic behavior might not be that of the real component processes at the microscopic level. The present study encourages one to weight this latter possibility with respect to the Stroop effect. One is not compelled to assume a processing conflict for the putative conflict at the behavioral level. This is certainly the option preferred by applying Occam's razor. We return to discuss this radical idea after reviewing our novel results at hand.

The Processing of Stroop Stimuli: Interaction in Color Classification versus Independence in Color and Word Detection

In the present series of 4 experiments, each observer performed in a Stroop task (classifying print colors) and in a target detection task (detecting the presence of a word or a color target) with the same set of color words printed in color as stimuli. The results showed that a Stroop effect reliably appeared in the color classification task: The color responses were faster to congruent than to incongruent stimuli in all experiments. The Stroop effect was particularly appreciable when the colors and the words were <u>not</u> matched on salience in advance (i.e., were mismatched in favor of the word dimension).

Notably, the same observers exhibited redundancy gain in the detection task: The responses were faster to displays containing redundant targets (both the word <u>and</u> the color target are present) than to displays containing a single target (only the word <u>or</u> the color target is present). However, the gain did not derive from an interaction in the processing of the target word and color (in the double target displays). It rather reflected the statistical facilitation accrued from the presentation of multiple targets each detected in an independent parallel fashion. Therefore, we found a Stroop effect in classification in tandem with a separate processing in detection for the same colors and words.

Concerning the results in the detection task, several features of the data supported the separate processing of word and color. In all the experiments, the race model inequality was not violated. This fact rules out high super capacity in the congruent-targets conditions. It argues against coactivation of the color and word signals since coactive models have been analytically proven to produce such violations (Townsend & Nozawa, 1995). The absence of any super capacity gauged by C(t) observed in all the experiments seals the case: Parallel models incorporating any significant positive interactions are falsified. The fine-tuned tests of architecture based on the mean- and survivor-interaction contrasts have consistently supported independent parallel races, too.

The closeness of C(t) to 1, the failure to violate the Grice bound in the incongruent color-word target conditions, along with the parallel minimum time conclusions with the SIC functions, also support standard (and non-interacting) parallel races, and disconfirm strongly inhibitory processes. Notable also in this respect is the finding that the identity of the targets (whether congruent or incongruent with the distractor) had no discernable effect on performance. Given an independent race, the color horse does not "know" of the position, speed, indeed of the very existence of the word horse. Consequently, the identity of the target or the distractor as well

as their semantic relationship do not play a role under a race architecture. Our results in the detection task are consistent with this architecture.

Can a Stroop Effect Arise When the Word and its Color are Processed along Separate Channels?

This intriguing question is virtually invited by the present outcome. Consider the data as a whole. How can one reconcile, indeed interpret the sets of results obtained with the focused- and the divided-attention tasks? A ready resolution is to reject the assumption of a common processing operation in the two tasks. Thus, the interference found in the Stroop task is the natural outcome of a coactive architecture. The lack of interaction in the detection task is a surprising result, tapping a race architecture. In this respect, we note the results obtained by Bauer and Besner (1997) in a focused-attention <u>detection</u> task. In their study, the participant detected the presence or absence of a red color in the stimulus (words did not serve as targets). The Stroop effect was absent from this color detection task although it was present in the routine color classification task performed by the same participants. This result can be taken to support the different architecture interpretation.

The other, remaining resolution forms a radical departure from existing accounts of the Stroop effect. On this account, the race model found for divided attention is also in force for focused attention. This is a provocative idea when one realizes that in this mode of processing there does not exist any platform for color and word to interact. Interaction is totally excluded in a separate decisions parallel race. As we just recounted, the color horse does not even "know" of the word horse and vice versa. If so, the putative interference in the behavioral Stroop effect is not sustained by a genuine interaction of the underlying processes. The question of consequence is this. Can a Stroop effect ensue under such a regimen?

The disheartening answer at this point is that we still do not know. Despite our investment in modeling, a generic parallel separate model for the Stroop effect has evaded us. The main difficulty we encountered was accounting for <u>both</u> RT and accuracy data. At this point, our developments can serve at best as an existence proof that the behavioral Stroop effect is possible under a race architecture (under a fairly restricted range of model parameters). Despite our failure thus far at modeling, we wish to provide a flavor of the pertinent ideas. So, we next present a scenario in which a Stroop effect emerges in the face of strictly parallel processing.

A Separate Channels Theory of the Stroop Effect[11]

The following five tenets define this admittedly inchoate theory. First, all the words and the colors included in the entire stimulus ensemble (presented and not presented on any particular trial) are activated on each trial. Second, perceived stimuli are processed more efficiently than those merely remembered from previous trials, although, again, all channels are activated on each and every trial. Third, the architecture is that of a strictly parallel race. The channels do not converge downstream, nor does exist a common decision mechanism fed by the various channels. Each channel processes its own input and races to produce a response determined entirely by the information it carries. Fourth, processing is stochastic, accomplished with imperfect accuracy. Error occurs when a channel other than that entailing the presented print color determines the response. Fifth, errors can nonetheless produce the correct response when the channel determining the response is that of the matching word (whether or not that word is presented for view); errors produce incorrect responses when one of the other color- or word-

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[11]We wish to reissue an important caveat in the outset: The following schema is not sustained by a rigorous quantitative model at this point. In particular, we failed in our efforts to develop a fully satisfactory (i.e., fully independent) model along these lines. The reader should bear this failure in mind when assessing the idea presented.

channels determines the response. Observable errors are discouraged by feedback from the experimenter (or nature).

Of course, the experimenter (or nature) creates the task itself, its demands, and the target attribute for responding. In the case of the Stroop task, the target attribute is the print color of the presented words. Correct responses (in and out of the laboratory) are rewarded (if by mere approval or reduced task time) and, conversely, incorrect responses are not rewarded or can carry unwanted consequences. Other than these trivial actions for setting the task framework, nothing more is required for generating the behavioral Stroop effect. Notably, one does not need an explicit parameter for prioritizing color over word processing (we had at one point included such a parameter in our model, but it proved gratuitous). The five tenets noted suffice to produce the Stroop effect.

Let us draw the consequences with respect to the Stroop effect. The standard result expected by the theory is that of a small Stroop effect. Given a color word in color exposed for view, the color and the word (as well as the other words and colors in the ensemble) engage in a race along separate channels. Because the stimulus components are processed in separate channels, the channel carrying the presented print color is indifferent to that carrying the presented word (and to all the other channels). Hence, the RT on Stroop-congruent trials does not differ from that on Stroop-incongruent trials when the channel with the target color determines the response. The quality of congruity simply does not carry psychological reality in a parallel race.

However, errors occasionally occur when a channel other than that carrying the target print color determines the response. The errors fall into two classes: observable and unobservable. Consider the congruent stimulus, RED in red, and the incongruent stimulus, GREEN in red. Note that the same channel (print color red) carries the correct response in both cases. Observable errors occur when the response is determined by the channel carrying the word GREEN or by that carrying the print color green. Unobservable errors occur when the responses are determined by the channel carrying the word RED. Such responses are indistinguishable from the responses produced by the channel carrying the print color red. Consider the two stimuli again. For the congruent stimulus, both the print color red and the color word RED are presented for view and count for the correct response. For the incongruent stimulus, the presented color red and the unexposed word RED count for the correct response. The RED channel thus carries perceptual information in the first case, remembered information in the second case. According to the second tenet of the theory, perceived stimulus components are processed more efficiently than remembered components. Therefore, the erroneous channel RED is processed more efficiently with congruent than with incongruent stimuli. The result is the behavioral Stroop effect.

According to this account, the Stroop phenomenon is parasitic on stochastic processing (there would be none under deterministic processing). Because errors constitute a minority of the responses, the Stroop effect is small (or absent) under the standard preparation in which the words and the colors are equally salient and appear at equal probability over the experimental trials (cf. Melara & Algom, 2003). However, standard preparations are uncommon in the literature. The vast majority of published Stroop reports entail systematic deviations from the standard preparation. The deviations act to exacerbate the difference between congruent and incongruent stimuli by way of producing the prototypical Stroop effect. The impact of the deviations -- also known as contextual factors (e.g., discriminability, correlation, response probability and mode) -- is easily discerned in terms of separate channel theory.[12]

We cannot discuss within the framework of this study (indeed within the confines of any single study) all the pertinent ramifications vis-à-vis the Stroop phenomenon. We thus elected to

address just one important issue here, namely, the typical results obtained when presenting neutral along with congruent and incongruent stimuli. Neutral trials include non-color words or non-words (e.g., XXXX) printed in color and often serve to partition to the Stroop effect into interference (the advantage of neutral over incongruent trials) and facilitation (the complementary advantage of congruent over neutral trials). An interesting question in the present context refers to interference. Why is performance slower in the incongruent than in the neutral condition?

Two factors conspire to produce this result in the present approach. First, base-time is longer in the incongruent than in the neutral condition due to the need to identify the semantic category of the Stroop stimuli. Stroop stimuli are those complex stimuli in which <u>all</u> components belong in the same semantic category. With Stroop's original stimuli, all components were associated with color. This shared meaning is the precondition enabling the creation of congruent and incongruent cases in the first place (observe: all conceivable combinations of a color word and a print color must result in a congruent or an incongruent stimulus). This feature is missing in the neutral condition because neutral stimuli are <u>not</u> Stroop stimuli (Algom, Chajut, & Lev, 2004). A lesser influence supporting faster overall responding in neural than in incongruent trials is the strains on capacity wrought by multiple targets included in the latter stimuli.

As a generic observation, neutral stimuli are a stranger in the Stroop environment, a fact that explains the great variability of interference and facilitation in the literature. There does not exist a consensual definition of what constitutes a 'neutral' stimulus in the first place (MacLeod, 1991). We also dispute the widespread notion that interference is necessarily larger than facilitation. As the analysis byMelara and Algom (2003, see especially pp. 437–438) shows, the difference between interference and facilitation is contingent, depending on a range of contextual variables.

Finally, we note that MacLeod and MacDonald have entertained an idea that bears some similarity to the present development (see MacLeod & MacDonald, 1998, 2000). They argued that facilitation was not "real" and resulted only from accidental inadvertent reading of the nominally irrelevant (yet helpful in the congruent condition) word. Our idea differs from MacLeod's in at least two important respects. First, our perspective envelopes the entire Stroop effect, not merely that portion called 'facilitation'. Second, in our development the effects are very real, the product of authentic and involved underlying processes.

Concluding Remarks

One should exercise caution before drawing strong conclusions especially in view of our unsuccessful modeling effort. Perhaps it would be premature to conclude that no model, out of all those offered heretofore, can simultaneously predict the strong behavioral interference associated with the traditionally focused attention Stroop task, and our present findings in the divided attention, both with incongruent and congruent stimulus dimension assignments. The challenge is non-trivial, given the dramatic reversal in moving from one paradigm to another. It does appear that models which place the primary interference toward the far end of

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[12]We cannot further expand on our ideas within the confines of this study or address several seemingly inconsistent results that come to mind from the vast Stroop literature. For instance, Dunbar and MacLeod (1984) found that the Stroop effect was unaffected when the words were presented in a transformed typography and/or in a vertical spatial position (both of which slowed down reading). Consequently, the authors questioned the relative speed of processing account of the Stroop effect. One should be careful not to take the relative speed of processing account for an independent race model. It is actually a coactivation model because word and color information coalesce in a common decision mechanism or response buffer. In a genuine independent race model, word and color never interact and each channel has its own separate decision mechanism. For another instance, non-color words that are semantically related to colors (sky, lemon, blood) have been shown to produce more Stroop interference than control words (Klein, 1964; but see Burt, 2002). This semantic contribution to the Stroop effect might necessitate relaxing strict independence (although not separate processing!) perhaps along the lines of the "interactive race model" suggested by Mordkoff and Yantis (1991; see also Miller, 1991).

processing, for example in a decisional or response selection mechanism, might better be able to negotiate the opposing results than early, maybe sensory inhibitory models. Time and more research will tell.

Acknowledgments

References

Algom D, Chajut E, Lev S. A rational look at the emotional Stroop phenomenon: A generic slowdown, not a Stroop effect. Journal of Experimental Psychology: General 2004;133:323–338. [PubMed: 15355142]

Algom D, Dekel A, Pansky A. The perception of number from the separability of the stimulus: The Stroop effect revisited. Memory & Cognition 1996;24:557–572.

Ashby FG, Townsend JT. Varieties of perceptual independence. Psychological Review 1986;93:154–179. [PubMed: 3714926]

Bauer B, Besner D. Processing in the Stroop task: Mental set as a determinant of performance. Canadian Journal of Experimental Psychology 1997;51:61–68.

Besner D. The myth of ballistic processing: Evidence from the Stroop paradigm. Psychonomic Bulletin & Review 2001;8:324–330. [PubMed: 11495121]

Burt JS. Why do non-color words interfere with color naming? Journal of Experimental Psychology: Human Perception and Performance 2002;28:1019–1038. [PubMed: 12421053]

Cohen JD, Dunbar K, McClelland JL. On the control of automatic processes: A parallel distributed processing account of the Stroop effect. Psychological Review 1990;97:332–361. [PubMed: 2200075]

Colonius H. Possibly dependent probability summation of reaction time. Journal of Mathematical Psychology 1990;34:253–275.

Colonius, H.; Townsend, JT. Activation-state representations of models for the redundant-signals-effect. In: Marley, AAJ., editor. Choice, decision, and measurement: Essays in honor of R. Duncan Luce. Hillsdale, NJ: Erlbaum; 1997. p. 245-254.

Dishon–Berkovits M, Algom D. The Stroop effect: It is not the robust phenomenon that you have thought it to be. Memory & Cognition 2000;28:1437–1449.

Dunbar K, MacLeod CM. A horse race of a different color: Stroop interference patterns with transformed words. Journal of Experimental Psychology: Human Perception and Performance 1984;10:622–639. [PubMed: 6238123]

Dyer FN. The Stroop phenomenon and its use in the study of perceptual, cognitive, and response processes. Memory & Cognition 1973;1:106–120.

Dzhafarov, EN. Process representations and decompositions of response times. In: Marley, AAJ., editor. Choice, Decision and Measurement: Essays in Honor of R. Duncan Luce. Mahwah, NJ: Erlbaum; 1997. p. 255-278.

Egeth HE, Dagenbach D. Parallel versus serial processing in visual search: Further evidence from sub-additive effects of a visual quality. Journal of Experimental Psychology: Human Perceptions and Performance 1991;17:550–559.

Garner, WR. The processing of information and structure. Potomac, MD: Erlbum; 1974.

Grice GR, Canham L, Gwynne J. Absence of a redundant-signals effect in reaction time task with divided attention. Perception & Psychophysics 1984;36:565–570. [PubMed: 6535102]

Klein GS. Semantic power measured through the interference of words with color naming. American Journal of Psychology 1964;77:576–588. [PubMed: 14255565]

Lindsay DS, Jacoby LL. Stroop process dissociations: The relationship between facilitation and interference. Journal of Experimental Psychology: Human Perception and Performance 1994;20:219–234. [PubMed: 8189189]

Logan GD. Attention and automaticity in Stroop and priming tasks: Theory and data. Cognitive Psychology 1980;12:523–553. [PubMed: 7418368]

Luce, RD. Response times. New York: Oxford University Press; 1986.

MacLeod CM. Half a century research on the Stroop effect: An integrative review. Psychological Bulletin 1991;109:163–203. [PubMed: 2034749]

MacLeod CM, Dunbar K. Training and Stroop-like interference: Evidence for a continuum of automaticity. Journal of Experimental Psychology: Learning, Memory, and Cognition 1988;14:126–135.

MacLeod, CM.; MacDonald, PA. Facilitation in the Stroop task is illusory: The inadvertent learning hypothesis. University of Toronto; 1998. Unpublished manuscript

MacLeod CM, MacDonald PA. Inter-dimensional interference in the Stroop effect: Uncovering the cognitive and neural anatomy of attention. Trends in Cognitive Sciences 2000;4:383–391. [PubMed: 11025281]

Melara RD, Algom D. Driven by information: A tectonic theory of Stroop effects. Psychological Review 2003;110:422–471. [PubMed: 12885110]

Melara RD, Mounts JRW. Selective attention to Stroop dimensions: Effects of baseline discriminability, response mode, and practice. Memory & Cognition 1993;21:627–645.

Miller J. Divided attention: Evidence for coactivation with redundant signals. Cognitive Psychology 1982;14:247–279. [PubMed: 7083803]

Miller J. Channel interaction and the redundant-targets effect in bimodal attention in bimodal divided attention. Journal of Experimental Psychology: Human Perceptions and Performance 1991;17:160–169.

Monahan JS. Coloring single Stroop elements: Reducing automaticity or slowing color processing? Journal of General Psychology 2001;128:98–112. [PubMed: 11277451]

Mordkoff JT, Yantis S. An interactive race model of divided attention. Journal of Experimental Psychology: Human Perceptions and Performance 1991;17:520–538.

Morton J, Chambers SM. Selective attention to words and colors. Quarterly Journal of Experimental Psychology 1973;25:387–397.

Pansky A, Algom D. Stroop and Garner effects in comparative judgment of numerals: The role of attention. Journal of Experimental Psychology: Human Perception and Performance 1999;25:39–58.

Pansky A, Algom D. Comparative judgment of numerosity and numerical magnitude: Attention preempts automaticity. Journal of Experimental Psychology: Learning, Memory, & Cognition 2002;28:259–274.

Posner, MI.; Snyder, CRR. Attention and cognitive control. In: Solso, RI., editor. Information processing and cognition: The Loyola symposium. Hillsdale, NJ: Erlbaum; 1975. p. 55-85.

Phaf RH, van der Heiden AHC, Hudson PTW. SLAM: A connectionist model for attention in visual attention tasks. Cognitive Psychology 1990;22:273–341. [PubMed: 2376113]

Raab D. Statistical facilitation of simple reaction time. Transactions of the New York Academy of Sciences 1962;43:574–590. [PubMed: 14489538]

Roelofs A. Goal-referenced selection of verbal action: Modeling attentional control in the Stroop task. Psychological Review 2003;110:88–125. [PubMed: 12529058]

Sabri M, Melara RD, Algom D. A confluence of contexts: Asymmetric versus global failure of selective attention to Stroop dimensions. Journal of Experimental Psychology: Human Perceptions and Performance 2001;27:515–537.

Schweickert R, Townsend JT. A trichotomy method: Interactions of factors prolonging sequential and concurrent mental processes in stochastic PERT networks. Journal of Mathematical Psychology 1989;33:328–347.

Stolz JA, Besner D. On the myth of automatic semantic processing. Current Directions in Psychological Science 1999;8:61–65.

Stroop JR. Studies of interference in serial verbal reaction. Journal of Experimental Psychology 1935;18:643–662.

Townsend JT. Some results concerning identifiability of parallel and serial processes. British Journal of Mathematical and Statistical Psychology 1972;25:168–199.

Townsend JT. Uncovering mental processes with factorial experiments. Journal of Mathematical Psychology 1984;28:363–400.

Townsend, JT.; Ashby, FG. Stochastic Modeling of Elementary Psychological Processes. Cambridge: Cambridge University Press; 1983.

Townsend JT, Honey CJ. Consequences of base time for redundant signals experiments. Journal of Mathematical Psychology 2007;51:242–265. [PubMed: 18670591]

Townsend JT, Nozawa G. Spatio-temporal properties of elementary perception: An investigation of parallel, serial and coactive theories. Journal of Mathematical Psychology 1995;39:321–360.

Townsend JT, Schweickert R. Toward the trichotomy method: Laying the foundation of stochastic mental networks. Journal of Mathematical Psychology 1989;33:309–327.

Townsend JT, Wenger MJ. A theory of interactive parallel processing: New capacity measures and predictions for a response time inequality series. Psychological Review 2004;111:1003–1035. [PubMed: 15482071]

Uttal, WR. Are reductive (explanatory) theories of face perception possible? Some speculations and some findings. In: Wenger, MJ.; Townsend, JT., editors. Computational, geometric, and process perspectives on facial cognition: Contexts and challenges. Mahwah, NJ: Erlbaum; 2001. p. 467-501.

Virzi RA, Egeth HE. Toward a translational model of Stroop interference. Memory & Cognition 1985;13:304–319.

Wenger MJ, Townsend JT. Basic tools for attention and general processing capacity in perception and cognition. Journal of General Psychology 2000;127:67–99. [PubMed: 10695952]

Zhang H, Zhang J, Kornblum S. A parallel distributed processing model of stimulus-stimulus and stimulus-response compatibility. Cognitive Psychology 1999;38:386–432. [PubMed: 10328858]

Appendix

Definitions of important terms from the current discussion. T is the random variable marking response time. The subscripts W and C refer to the Word and Color channels, respectively.

Term	Definition
Probability density function (pdf)	$f(t) = P(T = t)$
Cumulative distribution function (cdf)	$F(t) = P(T \leq t) = \int_0^t f(t')dt'$
Survivor function	$S(t) = P(T > t) = 1 - F(t)$
Hazard function	$h(t) = \dfrac{f(t)}{S(t)}$
Integrated hazard function	$H(t) = \int_0^t h(t')dt' = -\log[S(t)]$
Capacity coefficient	$C(t) = \dfrac{H_{WC}(t)}{H_W(t) + H_C(t)}$
Race Model Inequality (RMI)	$F_{WC}(t) \leq F_W(t) + F_C(t)$
Grice Inequality (GI)	$MAX[F_W(t), F_C(t)] \leq F_{WC}(t)$
Mean Interaction Contrast (MIC)	Each of the two curves in the factorial plot of the mean response time is represented by the difference in RT between the end points defining the curve. The MIC is the difference between the two differerences.
Survivor Interaction Contrast [SIC(t)]	Same as MIC but calculated for survivor function rather than the mean at each time bin, t.

A.

B.
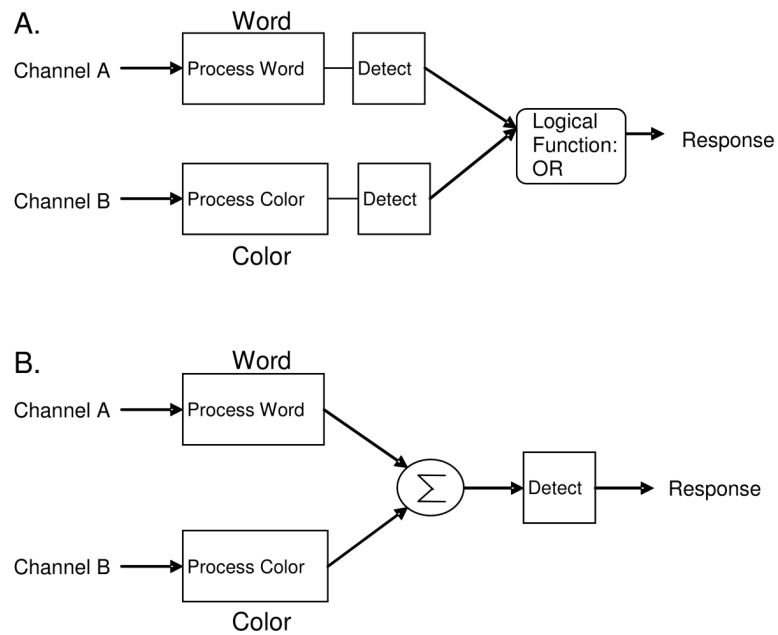
Figure 1.
Schemas for strictly parallel (A) and coactive (B) processing. For the parallel channels arrangement, detection is made separately for word and for color. The coactivation arrangement, by contrast, entails integration of information from the two channels in a common decision mechanism.
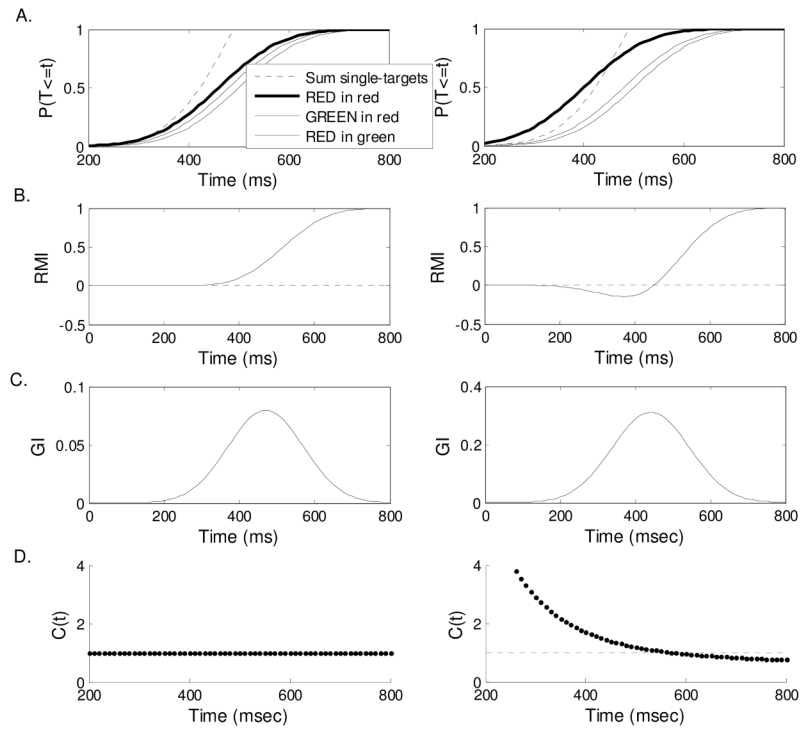
Figure 2.
Different predictions by separate channels (left column) and by interactive channels (right column) models. A: Families of cumulative density functions. B: Survivor function versions for testing the race model inequality (RMI). Violations of the inequality $S_{WC}(t) \geq S_W(t) + S_C(t) - 1$, expressed as negative values, correspond to violations of the race model inequality at that time. C: Survivor function tests of the Grice inequality (GI). Violations of the inequality $\min[S_W(t), S_C(t)] \geq S_{WC}(t)$, expressed as negative values, correspond to violations of Grice's inequality at that time. D: Capacity coefficient, $C(t)$, as a function of time.
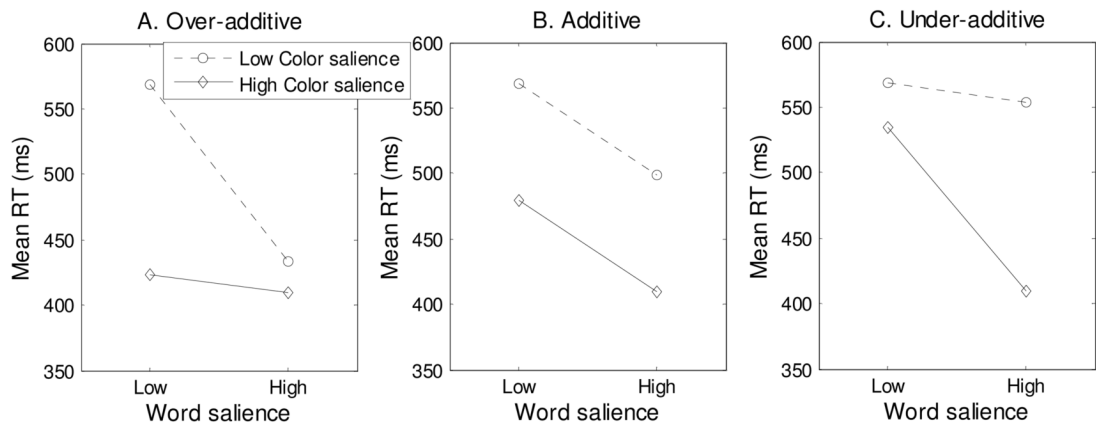
Figure 3.
Three possible outcomes of factorial experiments. The two variables are target type (color, word) and target salience (high, low).
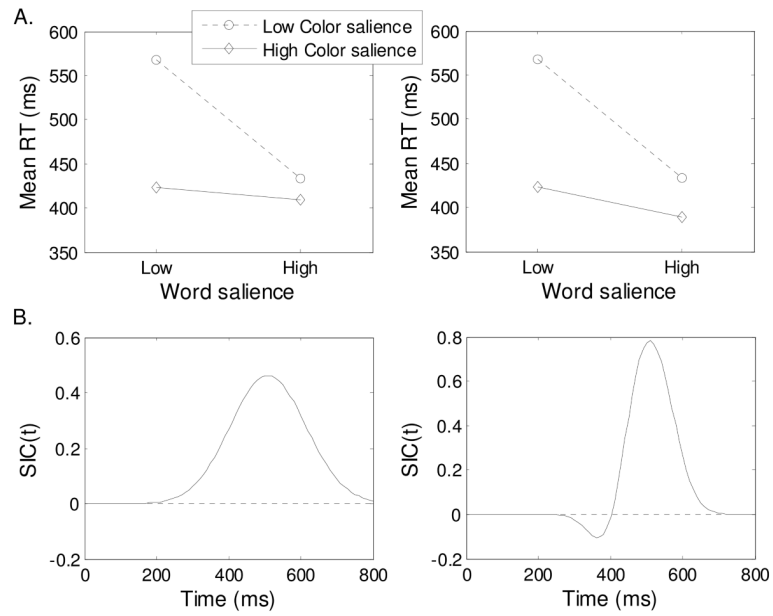
Figure 4.
Mean factorial plots (A) and SIC(t) functions (B). The predictions agree on A, but differ for B.
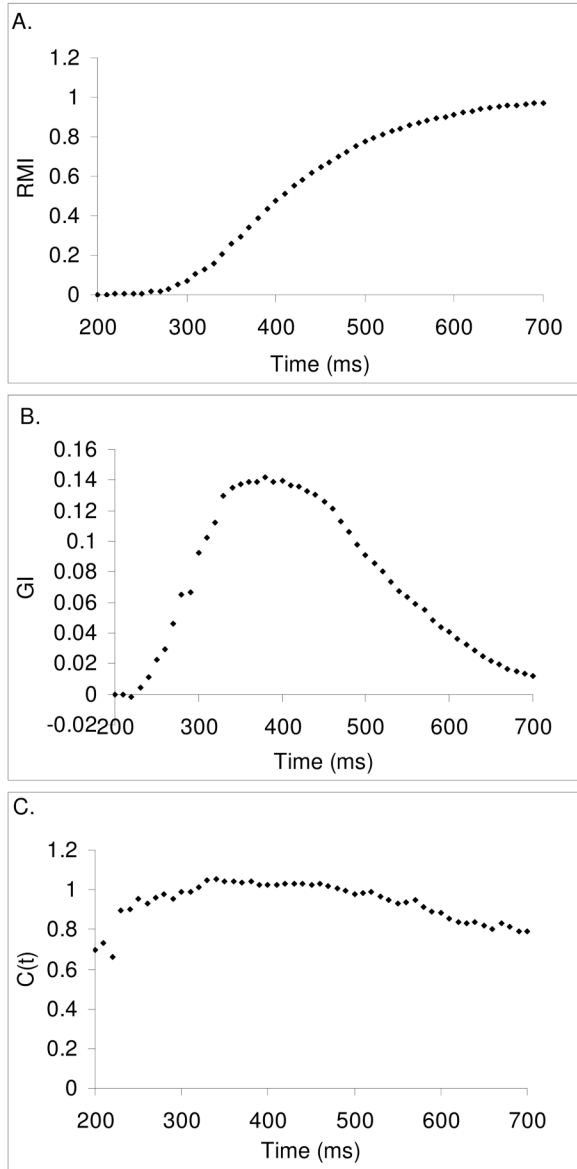
Figure 5.
Results of Experiment 1. A: Survivor function test of the race model inequality (RMI). Violations of the inequality $S_{WC}(t) \geq S_W(t) + S_C(t) - 1$, expressed as negative values, correspond to violations of the race model inequality at that time. B: Survivor function test of Grice's inequality (GI). Violations of the inequality $\min[S_W(t), S_C(t)] \geq S_{WC}(t)$, expressed as negative values, correspond to violations of Grice's inequality at that time. C: Capacity coefficients, $C(t)$, for Experiment 1.
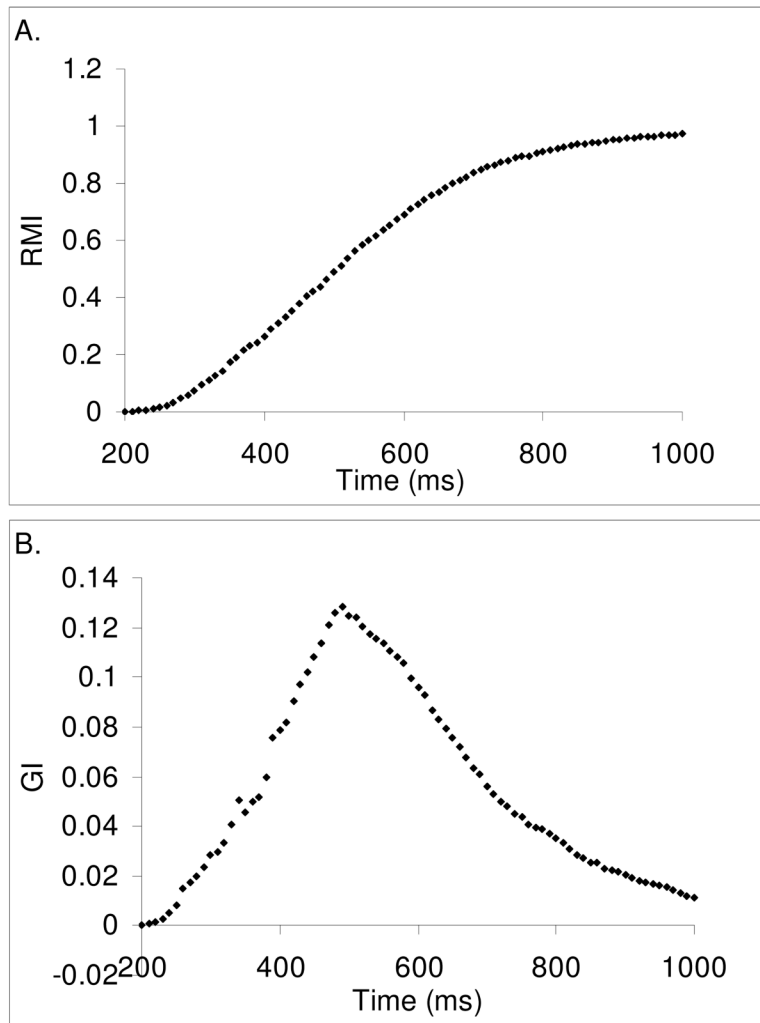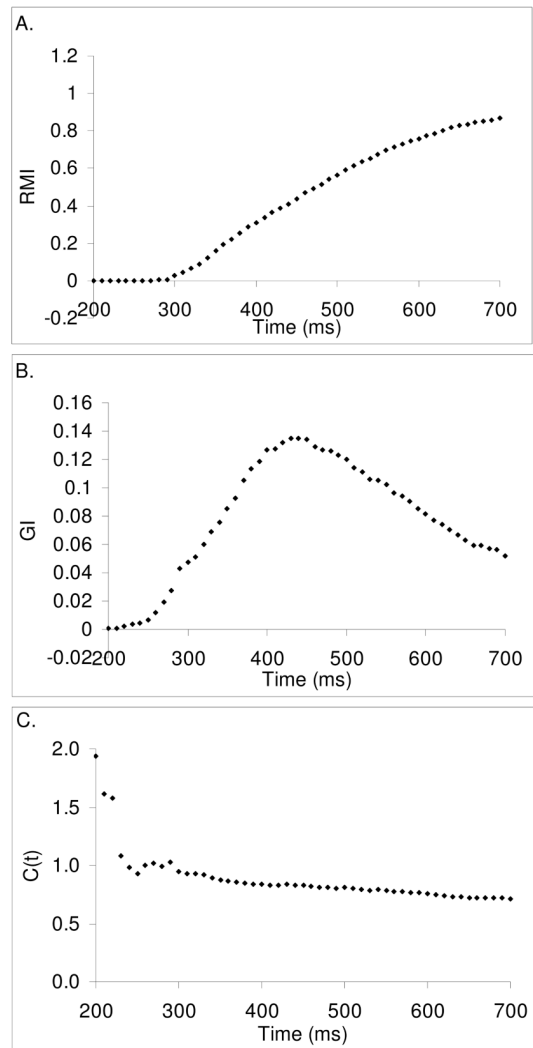
Figure 6.
Results of Experiment 2. A: Survivor function test of the race model inequality. B: Survivor function test of Grice's inequality.
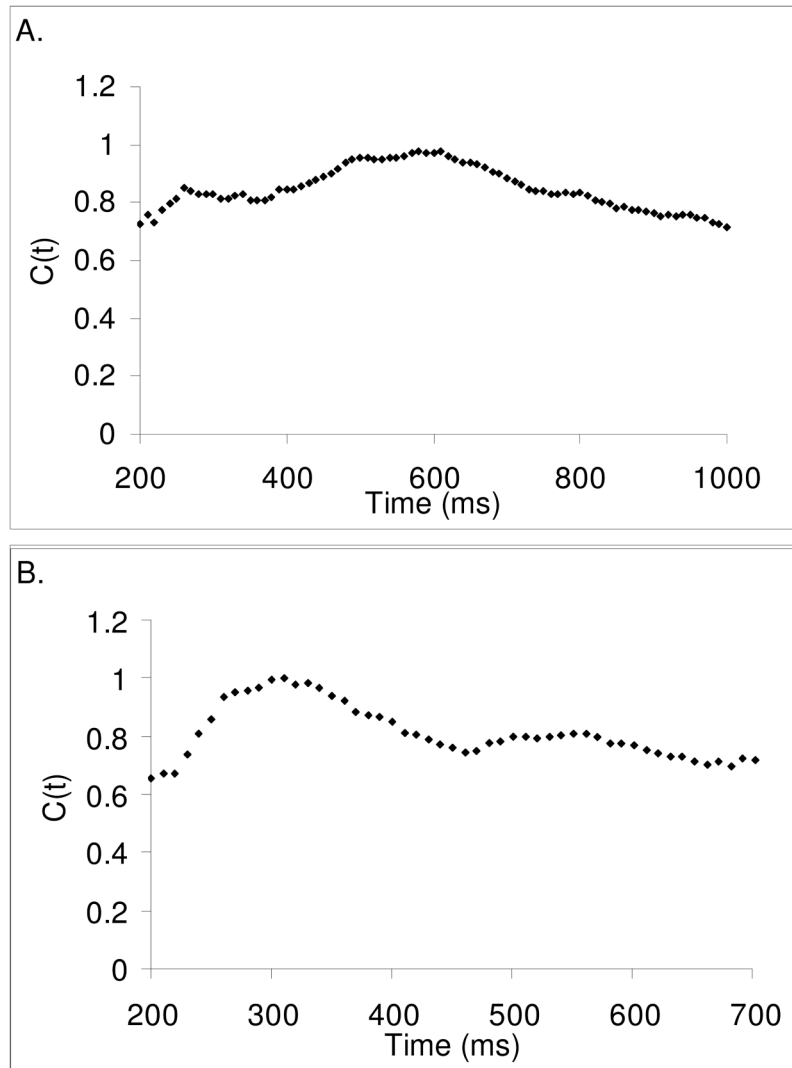
Figure 7.
Capacity coefficient, C(t), for data pooled over participants (A) and for an individual observer, participant 2 (B).
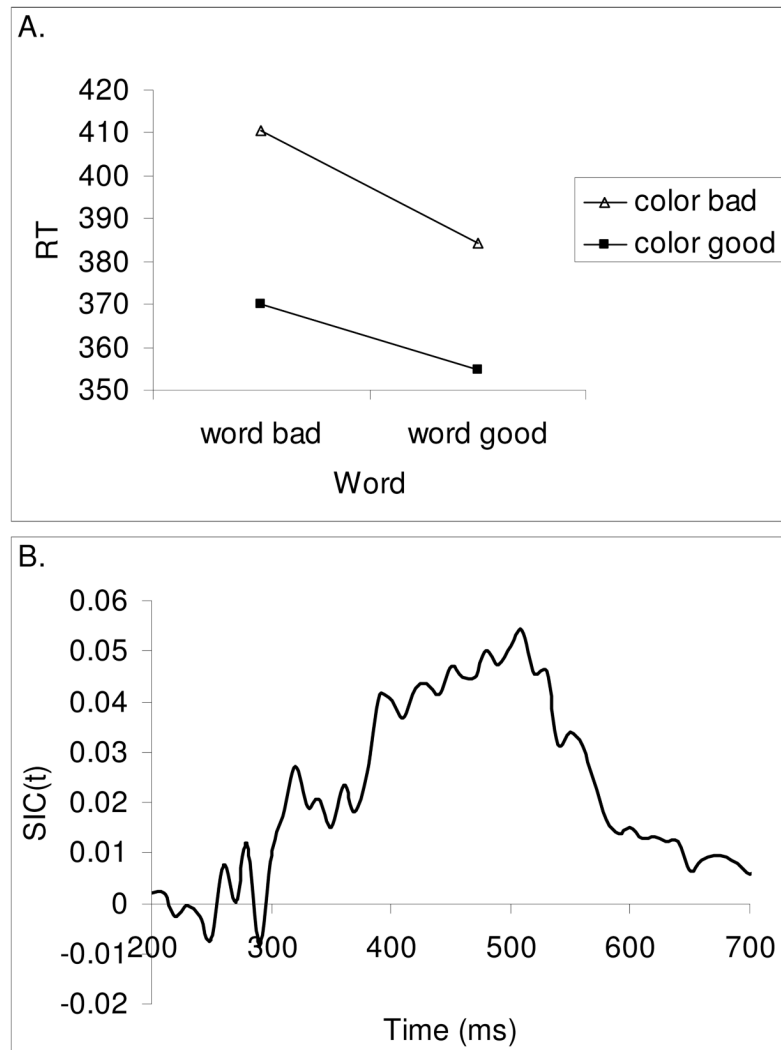
Figure 8.
Results from trials with redundant targets. A: Factorial plot of target (color, word) by salience (bad, good). B: Survivor interaction contrast, SIC(t), for the same data.
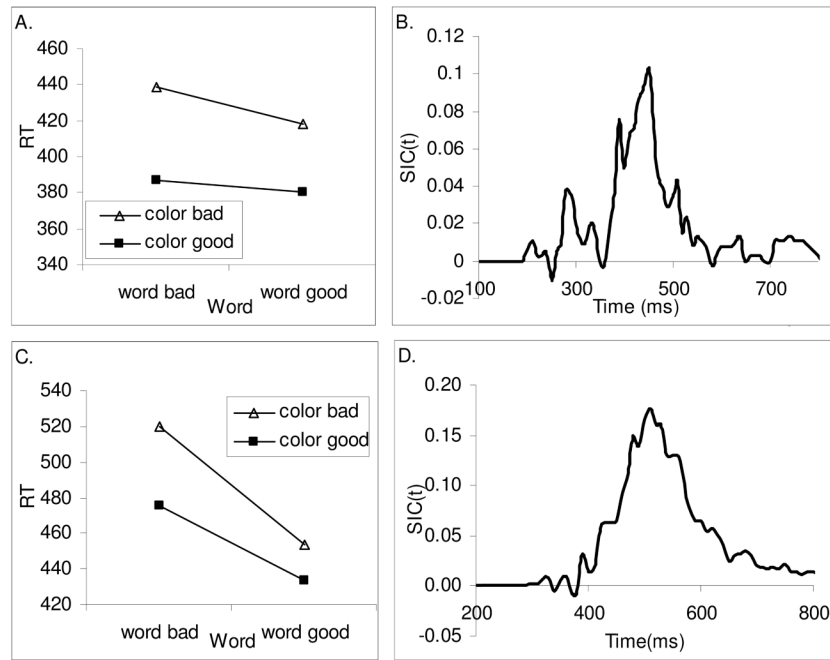
Figure 9.
Factorial plot for the subset of redundant-targets trials (A) and the associated survivor interaction contrast function (B) for Participant 3. Panels C and D provide the same results for Participant 5.
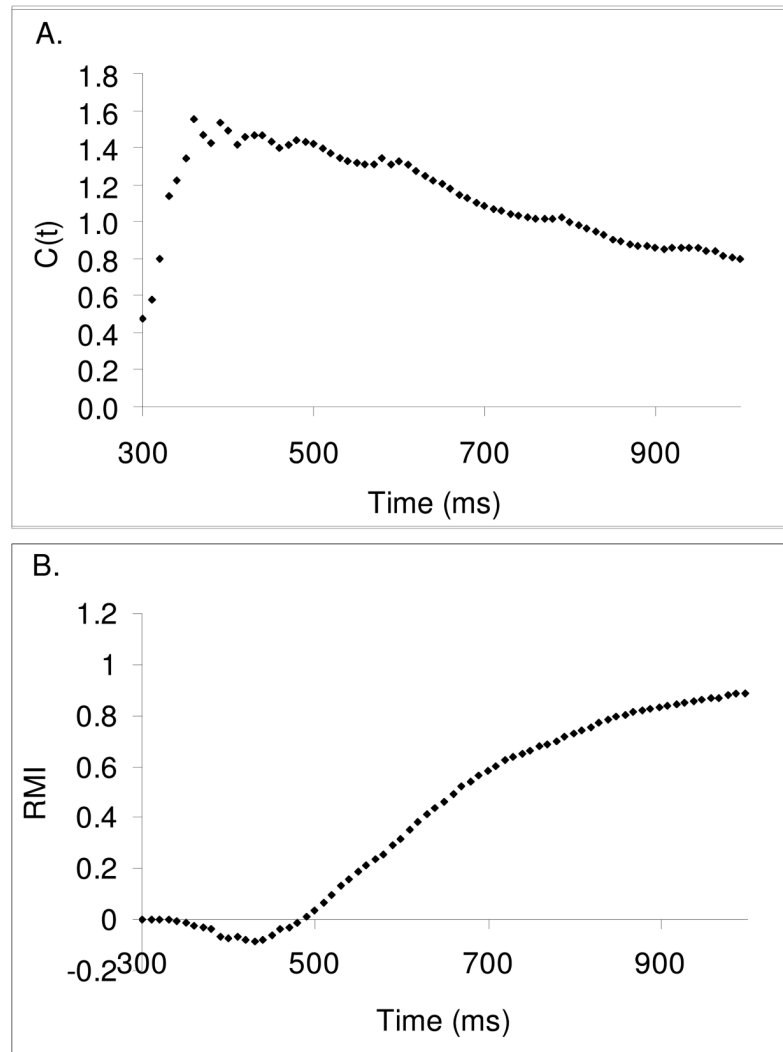
Figure 10.
Capacity coefficient (A) and race model inequality (B) for Participant 5.
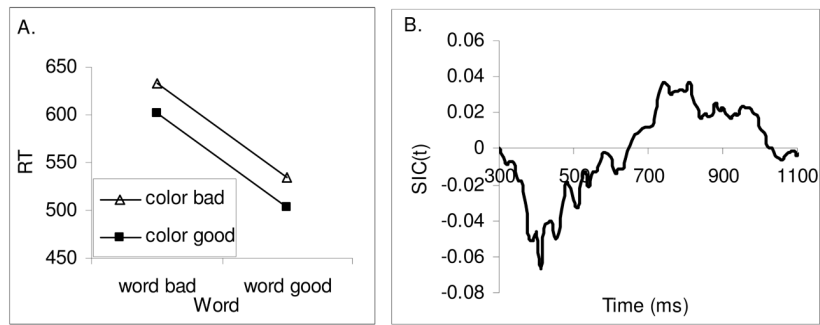
Figure 11.
Results of Experiment 2 for the subset of target-absent trials. Shown are the mean interaction contrast (A) and the associated survivor interaction contrast (B).

Figure 12.
Results of Experiment 3. A: Survivor function test of the race model inequality. B: Survivor function test of Grice's inequality. C: Capacity coefficient, C(t).
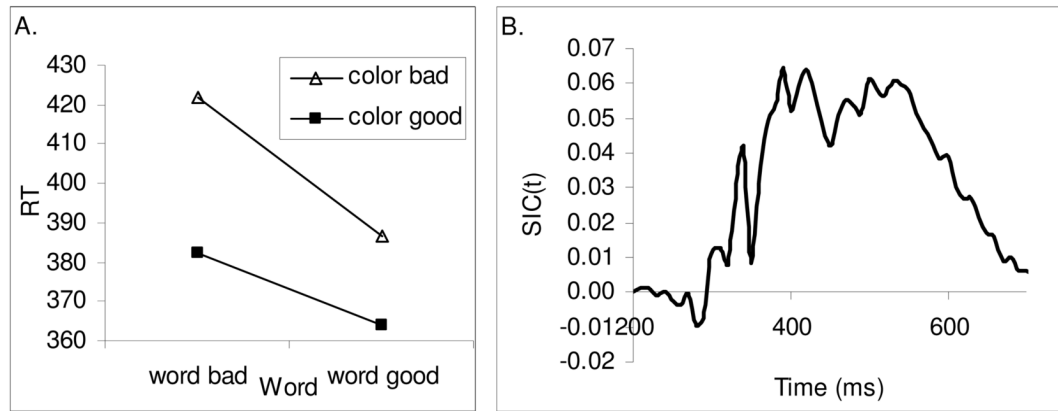
Figure 13.
Results of Experiment 3 considering only redundant targets trials. A: Factorial plot of target (color, word) × salience (high, low). B: Survivor interaction contrast, SIC(t), for the same data.
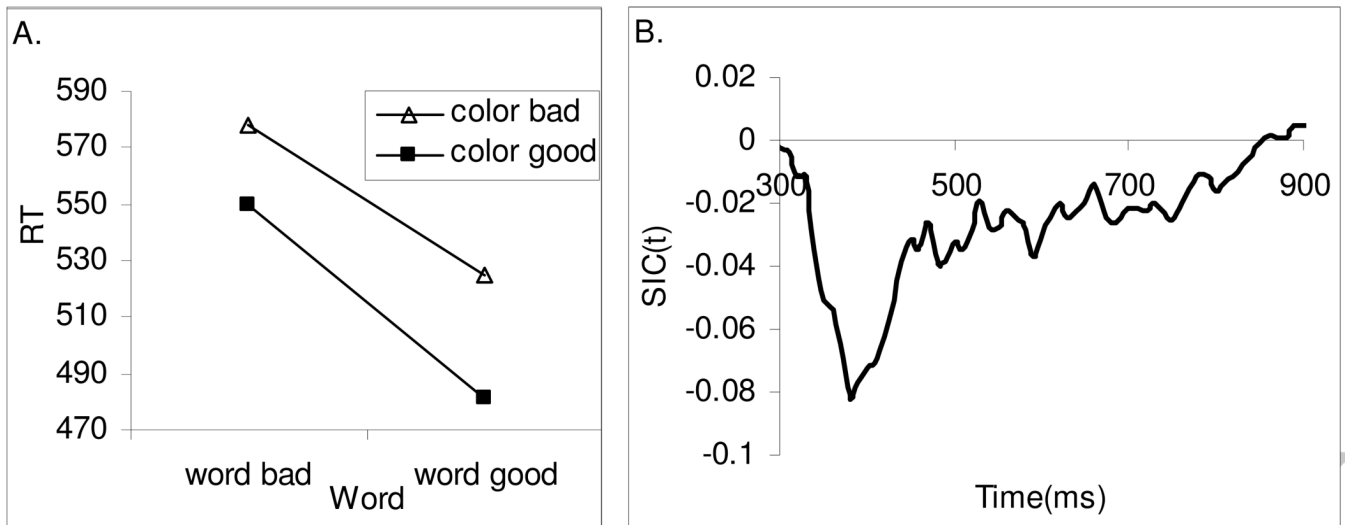
Figure 14.
Results of Experiment 3 for the subset of target-absent trials. Shown are the mean interaction contrast (A) and the associated survivor interaction contrast (B).
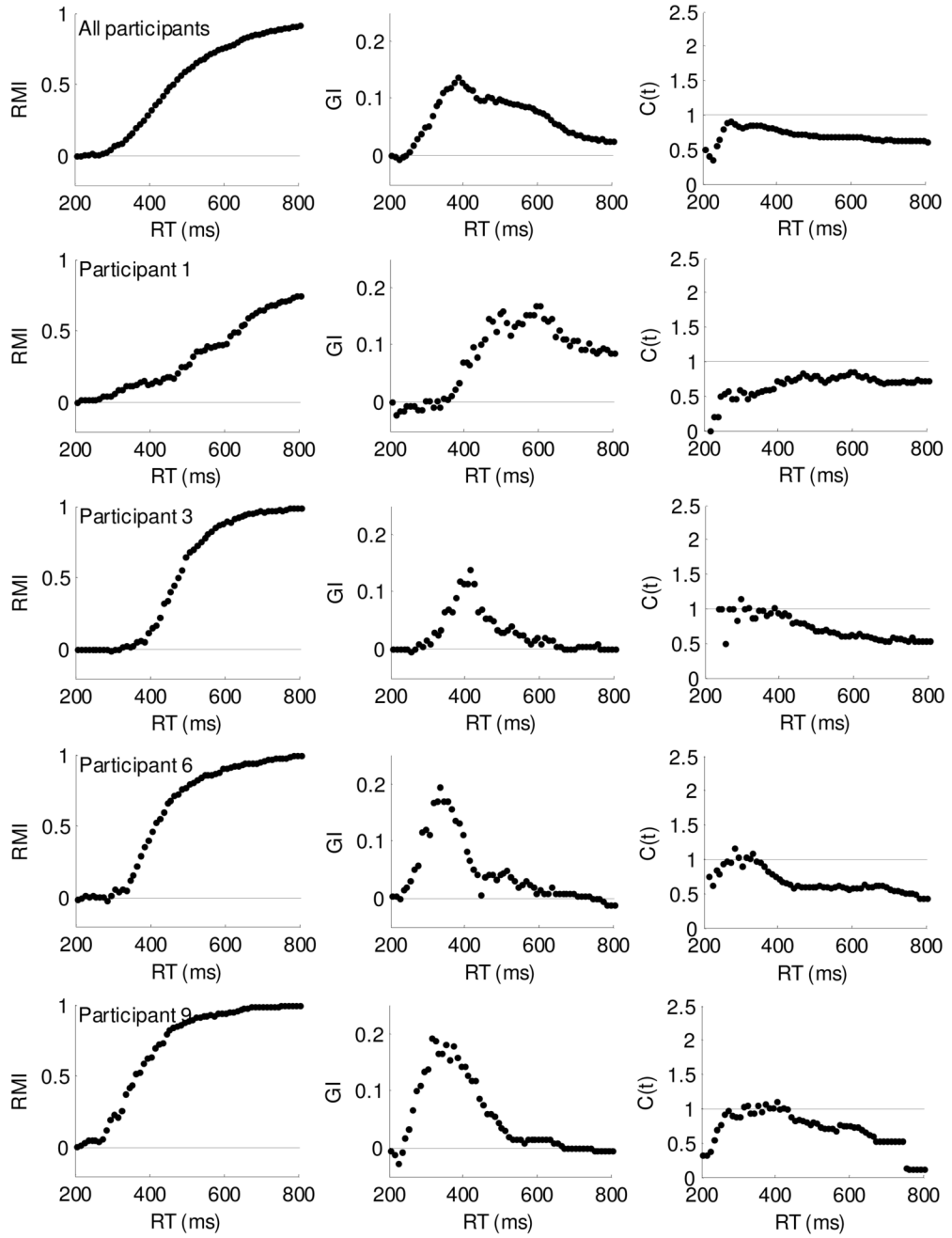
Figure 15.
Results of Experiment 4 in the target detection task, for the condition with RED and red as targets. The left column depicts the results with respect to the race model inequality (RMI). The middle column depicts the results with respect to the Grice inequality (GI). The right column presents the capacity coefficient, C(t). Top: all observers; Rows 2–5: data for individual observers 1, 3, 6, and 9, respectively.
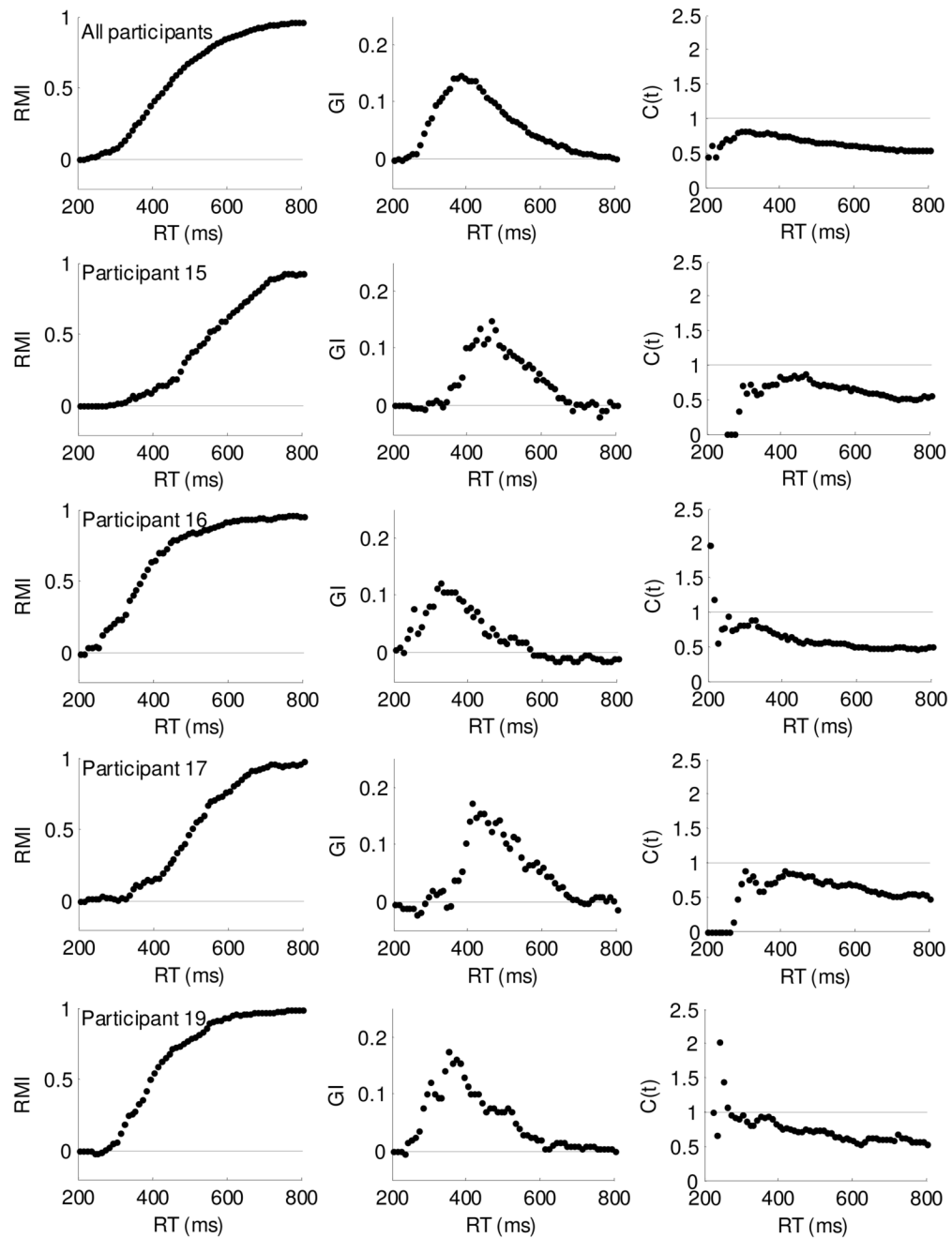
Figure 16.
Results of Experiment 4 in the target detection task, for the condition with RED and green as targets. The left column depicts the results with respect to the race model inequality (RMI). The middle column depicts the results with respect to the Grice inequality (GI). The right column presents the capacity coefficient, C(t). Top: all observers; Rows 2–5: data for indivual observers 15, 16, 17, and 19, respectively.

Table 1

Allocation of the same 4 stimuli (color words in color) into 2 response options (R1, R2) in color classification (Stroop) and target detection tasks.

		Stroop WORD			Target Detection WORD	
		RED	**GREEN**		**RED**	**GREEN**
COLOR	*red*	**R1**	**R1**	*red*	**R1**	**R1**
	green	**R2**	**R2**	*green*	**R1**	**R2**