

Stroop Process Dissociations: Reply to Hillstrom and Logan (1997)

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The Stroop counter model, which shares the assumptions of the application of process dissociation to the Stroop task presented by D. S. Lindsay and L. L. Jacoby (1994), is described in order to demonstrate the viability of these assumptions in quantitative models of the Stroop phenomenon. An experiment is presented to show converging evidence from applications of the process-dissociation procedure and the Stroop counter model. A demonstration of the Stroop counter model's ability to simulate both accuracy and response latency in the Stroop task is provided in the context of this experiment. Descriptions of the processing architecture in both the process-dissociation procedure and the Stroop counter model are provided, and issues of independence are discussed.

Lindsay and Jacoby (1994) proposed a process-dissociation (PD) procedure to characterize and measure the contributions of word-reading processes and color-naming processes to performance on the Stroop task. The PD equations that Lindsay and Jacoby used assume that word-reading processes and color-naming processes are functionally and statistically independent influences on performance and that the influence of word-reading processes dominates over the influence of color-naming processes when both influences simultaneously contribute to responding. As support for the assumptions of the equations and the viability of the PD procedure, Lindsay and Jacoby reported that (a) manipulating the color of items affected estimates of color-naming processes but not of word-reading processes; (b) manipulating the proportion of congruent versus incongruent items affected estimates of word-reading processes but not of color-naming processes; (c) estimates of color-naming processes were strongly correlated with color-naming performance on nonletter control strings; and (d) reducing the contribution of color-naming processes eliminated the typical asymmetry between interference and facilitation in response latency, just as the independence equations predict.

Hillstrom and Logan (1997) criticized Lindsay and Jacoby's (1994) PD procedure partly on the grounds that Lindsay and Jacoby did not offer a formal model that could account for effects in response times as well as accuracy. As Hillstrom and Logan noted, without such a model there are many ambiguities in the definition of terms and the general

approach offered by Lindsay and Jacoby. We have long been aware of these problems and have recently developed a model that extends the PD approach to account for effects in response times (Jacoby, McElree, & Trainham, in press). Work on this model has also led us to refine and clarify the definitions of key concepts of applications of the PD procedure to the Stroop task. Because the model incorporates the assumptions of the PD approach into a more complete model of Stroop processing, it constitutes a rebuttal to Hillstrom and Logan's critique.

A Counter Model of Stroop Effects on Response Latency and Accuracy

The Stroop counter model (Jacoby et al., in press) is similar to (and was inspired by) Ratcliff and McKoon's (1997) counter model of the effect of a prior presentation of a word on its subsequent perceptual identification. Furthermore, the Stroop counter model shares the continuous-processing conception of the model proposed by Cohen, Dunbar, and McClelland (1990). That is to say, rather than assuming that word-reading or color-naming processing must be completed at a discrete stage before information is available to later stages, we assume that partial processing influences performance.

The assumption that the outputs from word-reading and color-naming processes are combined additively is commonly used to justify subtracting performance on supposedly neutral items from that on congruent or incongruent items to compute facilitation and interference. The Stroop counter model, in contrast, assumes that influences from the two processes combine as specified by the independence equation in the decision-making system.

Description of the Stroop Counter Model

The model assumes that during each discrete interval of time (a cycle in the model), a single count (a piece of

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evidence or increment of influence toward a response) is acquired by one of a set of response counters, each of which corresponds to a potential color-naming response. The probability that a count is allocated to the target response counter at a given iteration because of the influence of word-reading processes (W) and color-naming processes (C) is $p(\text{correct/congruent}) = W + C(1 - W)$ for congruent stimuli and $p(\text{correct/incongruent}) = C(1 - W)$ for incongruent stimuli. These equations are the same as for the PD procedure but are applied to determine the allocation of counts over time within a trial, rather than to estimate the influences of W and C on overall overt performance. When neither W nor C determine the allocation of the count (with probability $(1 - C)(1 - W)$), the count for that cycle is randomly allocated to one of the counters in the response set (guessing). The counter model continues to accumulate evidence until one response counter obtains K (criterion) counts more than every other response counter. Response time is reflected in the number of iterations (cycles) that the model needs to select a response, given this decision rule.

The simultaneous modeling of response deadline (accuracy) data and response latency data requires an explicit treatment of the dynamics of processing. The evidence provided to the decision-making system from C is assumed to take the form of a cumulative gamma function. This is consistent with a continuous-flow conception (Eriksen & Schultz, 1979), which assumes that information about stimuli gradually accumulates from each process and that the output from each process becomes increasingly more detailed or exact over time.

$$C(t) = \frac{\beta^\alpha}{(\alpha - 1)!} \int_0^t t'^{\alpha-1} e^{-\beta t'} dt. \quad (1)$$

Standard interpretations of the Stroop task assume that the onset of a word stimulus triggers word-reading operations. It has been suggested that word-reading operations may produce interference because of compatibility between the word dimension of the stimulus and the structure of the response in the standard Stroop task (Treisman & Fearnley, 1969) and that this interference may be altered if the stimulus-response compatibility is altered (Flowers, Warner, & Polansky, 1979; Fox, 1992). The role of attention in the Stroop counter model is to select one of the two processes on the basis of the task instruction. Whereas stimulus-response compatibility triggers word-reading operations in the standard Stroop task, attention serves to suppress or inhibit this irrelevant source of information. The rationale for the input function of W is that the influence of word-reading processes must be filtered or suppressed by an attentional-control mechanism because of the task demands of the Stroop task. Sperling and colleagues (Reeves & Sperling, 1986; Sperling & Weichselgartner, 1995; Weichselgartner & Sperling, 1987) suggested that an attentional gating mechanism can be modeled by a gamma density function. The input from W is assumed to take the form of a nonmonotonic input function, a gamma density function, which instantiates the notion that influence from W grows over time to some peak value and

then diminishes because of the gating mechanism.

$$W(t) = \frac{\beta^\alpha t^{\alpha-1} e^{-\beta t}}{(\alpha - 1)!}, \quad t \geq 0. \quad (2)$$

Both input functions assume that color-naming and word-reading processes are products of the output from a number of component stages or processes (α), the strength of each of which is (identically) exponentially distributed with rate (β).

Viability of the Stroop Counter Model

To provide a test of the Stroop counter model and to provide a comparison with applications of the PD procedure to the Stroop task, Jacoby et al. (in press) conducted an experiment examining the effects of proportion congruency on both accuracy and latency of naming responses. In one condition, participants were required to produce their color-naming response before a short deadline of 550 ms. In the other condition, performance was measured in terms of response latency without a response deadline. For both conditions, the Stroop stimuli were the words *blue*, *yellow*, *green*, and *white* and strings of percentage signs (%%%) or %%%%). The proportion congruency was manipulated in an item-specific way by making two binary pairs of the four colors (e.g., blue-yellow and white-green). For congruent trials, the color name matched the color of the Stroop stimulus (e.g., *blue* in blue letters). For incongruent trials, the word was the other member of the binary pair (e.g., *yellow* in blue letters). For one binary pair (e.g., *blue* and *yellow*), trials were congruent 80% of the time, whereas for the other binary pair (e.g., *white* and *green*), trials were congruent 20% of the time. The overall proportion of congruent trials was 50% at the list-wide level.

Applications of the PD procedure require large differences in accuracy for congruent versus incongruent items in order to estimate the independent influences of W and C in the task. This is achieved by forcing participants to respond prior to a short deadline (in one condition of this experiment, 550 ms). The estimates of W and C obtained by application of the PD procedure provide a summary-level description of the influences of the processes during the trial. If both facilitation and interference are the result of the independent contributions of W and C and if the manipulation of proportion congruency affects only word-reading processes, then use of the PD procedure should reveal an effect of the manipulation on W and invariance in C . By applying the PD equations to results from the deadline condition, Jacoby et al. (in press) estimated W and C for both mostly congruent and mostly incongruent items (right-hand columns in Table 1). Manipulating proportion congruency in an item-specific manner reliably affected the estimated contribution of W but did not have an effect on the estimated contribution of C . These findings replicate those obtained by Lindsay and Jacoby (1994) when proportion congruency was manipulated between participants and further support the hypothesis that word reading and color naming act as independent sources of influence in the Stroop task.

The Stroop counter model is not constrained to situations

Table 1
Empirical and Simulated Results of Item-Specific Proportion-Congruency Experiments

Condition	Item type			Estimates	
	Congruent	Neutral	Incongruent	Color naming	Word reading
Deadline condition (% of correct responses before deadline)					
80% Congruent	88 (86)	68 (69)	33 (31)	73 (69)	55 (55)
20% Congruent	79 (78)	70 (69)	48 (50)	70 (69)	31 (28)
Response latency condition (latency of correct responses, in ms)					
80% Congruent	597 (595)	634 (645)	747 (740)		
20% Congruent	637 (622)	655 (646)	688 (690)		

Note. Numbers in parentheses are the simulated results generated by the Stroop counter model.

in which large differences in accuracy for congruent versus incongruent items exist. It is able to account for differences in accuracy and response time in both deadline and response latency versions of the Stroop task. The input functions representing the influences of W and C in the counter model provide a within-trial description of the temporal dynamics of the processes during the trial. That is to say, the influence of W and C is not summarized across the course of the trial to provide summary-level parameters of influence but is specified cycle by cycle across the course of the trial. Jacoby et al. (in press) used the Stroop counter model to fit the response latency data to fix temporal properties of the model and then examined whether the model could fit the response deadline (accuracy) data by varying only one parameter (K) in the model. This is consistent with the notion that participants lower their response threshold when placed under time pressure. The parameters for the nonmonotonic gamma density function for word-reading processes were set such that the rise time of the W function roughly matched the rise time of the C function, consistent with the notion that the two processes operate in parallel. Input functions used by Jacoby et al. to fit the results of varying the proportion of congruent items are shown in Figure 1. Because the results from the application of the PD procedure to the participants' data indicated that the proportion congruency manipulation affected W, the authors scaled the height of the W functions in the model such that the function for the mostly incongruent items was below the function for the mostly congruent

items.¹ This was the only parameter that was changed to account for the item-specific proportion congruency manipulation.

Jacoby et al. (in press) found that the Stroop counter model produced extremely good fits to the response latency data with a simple linear mapping function of iterations to experimental time. Table 1 shows the predicted and observed mean latencies for a correct response from the response-time variant of the task. The predicted latencies represent the average of 10,000 simulated trials per condition. The authors tested the simulated results from the model against the response-time distributions collected by Spieler, Balota, and Faust (1996) and found that the model rather precisely fit the shapes of the response-time distributions for congruent, neutral, and incongruent Stroop conditions.

To fit the response deadline (accuracy) data, Jacoby et al. (in press) set a simulated deadline of 40 iterations (corresponding to the 550-ms deadline used in the experiment) based on the iteration-to-time scaling used to fit the response latency data, reduced the criterion K , and then computed the number of correct responses that the model produced by the deadline after 10,000 simulated trials per condition. The input functions for the influences of W and C in the application of the model to the response deadline data were identical to the functions used in the response latency fits. Table 1 shows the observed and predicted accuracy values, which were extremely close to one another.²

Descriptions of Processing Architecture in the PD Procedure and the Stroop Counter Model

The PD procedure and the Stroop counter model share the assumptions that two independent sources of influence

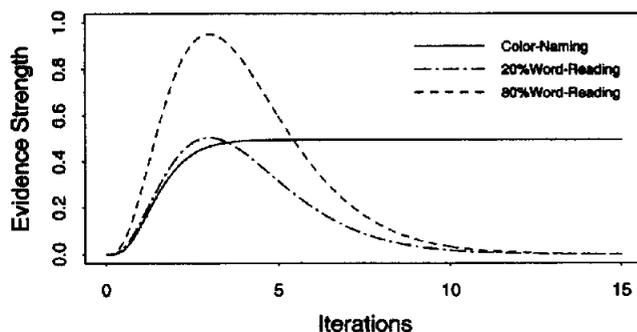


Figure 1. Input functions of word reading and color naming used by the Stroop counter model for two levels of proportion congruency (as a function of evidence strength across iterations in the model).

¹ The choice of the particular functions was largely arbitrary, guided by the goal of obtaining a good fit to the response time data and the post hoc estimates provided by Lindsay and Jacoby (1994). More needs to be done to develop a principled basis for the choice of functions.

² A chi-square test to determine whether the empirical cell means were significantly different from the simulated cell means in response latency conditions was not significant, $\chi^2(2, N = 24) = 0.686, ns$. A second chi-square test for cell means in deadline conditions measuring accuracy also was not significant, $\chi^2(2, N = 24) = 0.999, ns$. Furthermore, the model accounts for 98.7% of the between-cell variance in response latency conditions and 97.4% of the between-cell variance in deadline conditions measuring accuracy.

underlie performance on the Stroop task and that the influence of *W* dominates that of *C*. The two approaches differ in the level of analysis. The counter model describes the processing dynamics within trials. Those dynamics are affected not only by the influences of *W* and *C* during any given cycle but also by parameters of the input functions, the criterion *K*, and the speed with which the cycle occurs. The PD procedure, in contrast, provides summary-level descriptions of the influences of *W* and *C* collapsed across trials. Regardless of the dynamics within a trial, at the level of complete trials any given overt response (or any given failure to respond) can be ascribed to the independent influences of *W* and *C*. The two approaches provide converging support for the hypothesis that word-reading and color-naming processes serve as independent bases for responding in the Stroop task. Coordinating the PD procedure with the counter model provides more precise meanings for parameters and for the assumption of dominance in the PD procedure.

Definitions of W and C

For applications of the PD procedure, *W* and *C* can be interpreted as a summary-level description of the influences of word-reading processes and color-naming processes on the response selection component of the decision-making system collapsed across the level of a single trial. The PD procedure assumes that during congruent trials, the decision-making system produces a correct response based on the influence of *W* plus the influence of *C* multiplied by the complement of the influence of *W* [i.e., $W + C(1 - W)$]. Furthermore, during incongruent trials, the decision-making system produces a correct response based on the influence of *C* multiplied by the complement of the influence of *W* [i.e., $C(1 - W)$]. In the PD procedure, each of these estimates is represented by a single value from 0 to 1 representing the degree of influence from that basis for responding.

W and *C* do not refer to the probability of completion of word reading or color naming as they would if Stroop performance was described by a horse-race model, such as the model used by Logan (1988) to describe automaticity. If these estimates did refer to the completion of word-reading or color-naming processes, then one would not predict differences in response time between correct responses on incongruent items (when color-naming processes "finished" but word-reading processes did not "finish") and correct responses on neutral items (when color-naming processes "finish"). Given that there are large and robust differences in the latencies of correct responses to incongruent versus control items, a simple horse-race model cannot provide an adequate account of Stroop performance. However, a continuous-flow conception, assuming the gradual accumulation of information from each process, is consistent with our definition of *W* and *C* given that these estimates refer to a summary-level description of the influence from word-reading and color-naming processes. For applications of the Stroop counter model, a continuous-flow conception is built into the processing architecture, and the influences of *W* and *C* are specified as functions that change over time.

As Hillstrom and Logan (1997) noted, the stochastic-independence assumption is plausible when *W* and *C* are described as influences. Contrary to their claims, however, defining *W* and *C* as influences does not render the PD estimates uninterpretable. Using the PD equations and procedure, one can estimate the influences of word-reading and color-naming processes from probabilities of responding correctly within a deadline. Furthermore, using the PD equations and estimates obtained through an application of the PD procedure, one may predict the probabilities of responding correctly on congruent and incongruent trials at the same deadline from these estimates. The fact that estimates of *W* and *C* represent influences rather than probabilities does not disallow prediction of the probability of responding correctly on a Stroop trial.

Dominance of W Over C

Lindsay and Jacoby (1994) assumed that *W* dominates over *C*. That is to say, the decision-making system is influenced by color-naming processes only to the extent that it is not influenced by word-reading processes. Hillstrom and Logan (1997) claimed that there is no justification for this assumption. However, it seems reasonable to begin with the working assumption that in Stroop tasks with vocal responding of the color name, the presentation of a color-word stimulus triggers word-reading operations because of stimulus-response compatibility between the word dimension and the type of response. This interpretation of Stroop interference does not conflict with notions that word-reading processes are automatically engaged in during the Stroop task: on the contrary, it specifies necessary task-related characteristics for word-reading processes to be automatically invoked.

The dominance assumption and the input functions selected for the component processes in the counter model are compatible with Hillstrom and Logan's (1997) point that responding on the basis of automatic processes can be avoided. Although word-reading processes are believed to be dominant because of the compatibility of the stimulus dimension and the response, the influence of those processes is suppressed across time by task demands (attentional mechanisms) such that, when given sufficient time during incongruent trials, participants most often avoid mistakenly responding with the color-word and correctly respond by giving the color name. Until the influence from word-reading processes has been suppressed by attentional mechanisms, it serves to speed the production of a correct response for congruent items and slow the production of a correct response (or cause the production of an incorrect color-word response) for incongruent items.³ Measuring performance in terms of latency of correct responses leads to longer

³ The fact that word-reading processes can influence performance by slowing the production of a correct response for incongruent items (hence lowering the probability of any overt response within a deadline to incongruent items) explains why Lindsay and Jacoby (1994) did not make their analyses conditional on overt responses.

latencies for incongruent than for congruent items; measuring performance in terms of accuracy within an appropriate deadline leads to higher accuracy for congruent than for incongruent items.

The data patterns produced when the influence of word reading is assumed to dominate that of color naming are intuitively sensible; moreover, all of the findings cited as support for the PD approach to Stroop effects (i.e., a double process dissociation, strong correlations between C and color-naming performance on nonletter control items, and the relationship between C and the degree of asymmetry between facilitation and interference) provide support for the assumption. In contrast, as Hillstrom and Logan (1997) showed, assuming that the influence of color naming dominates that of word reading results in a variety of strange findings, such as that the influence of W is consistently greater than that of C on a color-naming task and that reducing the discriminability of the colors affects W as much as C.

We agree with Hillstrom and Logan (1997) that more needs to be done to understand the factors that affect the relative dominance of automatic versus controlled processes. Hay and Jacoby (1996) manipulated the congruency of memory-test items with prior training and used a process dissociation approach to separate the contributions of habit and recollection to memory performance. Their equations treated the contribution of controlled processes (recollection) as dominant over that of automatic processes (habit)—an assumption opposite to that made for Stroop performance. The assumption of dominance has been made on intuitive grounds. There are seemingly important differences between situations in which proactive interference and Stroop interference are found. In situations in which proactive interference is found, the automatic influences of prior presentations might serve largely as a source of educated guesses. Jacoby et al. (in press) described this type of automatic influence as accessibility bias, in which prior presentation changes the accessibility of categories or responses. For memory decisions, recollection is more "trustworthy" than habit or familiarity. Word reading in Stroop tasks seems to be a different, more compelling basis for responding than automatic processes (habit or familiarity) in memory tasks. Because of the stimulus-response compatibility between the irrelevant dimension and the type of response (and the lack of stimulus-response compatibility between the relevant dimension and the type of response) in the Stroop task, the processing of the irrelevant dimension provides a reflex-like basis of responding until attention serves to gate the influence from these processes. We see the relationship between the characteristics of the task and the dominance of component processes as a target for research and theorizing rather than as a reason to dismiss the PD procedure.

Influence of Guessing and Qualitative Changes Produced by Deadlines

Hillstrom and Logan (1997) contended that, in cognitive tasks in general, participants are more likely to guess under fast than under slow deadlines. As Hillstrom and Logan

pointed out, it is possible to incorporate a guessing component into the PD equations on the basis of the assumption that guessing occurs when neither W nor C influences responding. The Stroop counter model described above incorporates just such a mechanism. The model predicts that responses that are neither the name nor the color of an item are relatively likely when deadlines are extremely short because of the paucity of item-specific word and color information accrued within the deadline. Yonelinas and Jacoby (1996) discussed means of extending the process-dissociation approach to accommodate effects of guessing. They noted that effects of guessing will not necessarily perturb findings of process dissociations. That is, the absolute values of parameters can be in error because of not taking guessing into account without changing the pattern of results, i.e., the finding of process dissociations.

Our strategy has been to avoid or minimize the effects of guessing. Hillstrom and Logan (1997) showed that, relative to no deadline, a 400-ms deadline produced qualitative changes in performance (primarily by increasing the rate at which a subset of participants "guessed," as indicated by responses that were neither the name nor the color of an item), but they also showed that a 700-ms deadline [similar to Lindsay & Jacoby's (1994) deadline] had little or no effect. Effects of guessing and qualitative changes in processing produced by very short deadlines do create potential problems for the PD procedure and require further investigation, but we know of no other model of performance in Stroop tasks that addresses those issues. Indeed, other models (e.g., Logan, 1980) describe only effects on response time, ignoring any differences in accuracy (including, but not limited to, differences in accuracy produced by the effects of guessing). Partly because of our interest in action slips (e.g., Reason, 1979), which sometimes reflect the requirement of fast responding, we think it is important to account for differences in accuracy as well as effects on response time.

What Does It Mean to Be Independent? Functional Versus Stochastic Independence

Our research has emphasized findings of functional independence, showing that the parameters in the PD procedure can be selectively influenced. Our strategy has been to select manipulations that, on empirical and theoretical grounds, are expected to affect one process but not the other; if such a manipulation affects the appropriate parameter estimate while leaving the other invariant, the findings support the hypothesis that the two processes are independent. For example, manipulating proportion congruent affects the estimate of W but not of C, whereas a secondary task or a manipulation of color discriminability affects the estimate of C but not of W.

Following others (e.g., Tulving, 1984), Hillstrom and Logan (1997) distinguished between functional dissociations and stochastic independence. Furthermore, they argued that Lindsay and Jacoby's (1994) findings are evidence of functional independence but that they are irrelevant to an assumption of stochastic independence. Their argument is

incorrect. Lindsay and Jacoby's demonstrations are of functional independence of parameters whose estimates are based on the assumption of stochastic independence. If the underlying assumption of stochastic independence were badly violated, we would be unable reliably to find process dissociations. Indeed, showing a selective influence on parameters is the only way to test an underlying assumption regarding independence (Jacoby & ShROUT, 1997). Our approach is the same as that taken by advocates of signal-detection theory to provide evidence for the independence of discriminability and bias by showing that parameters representing discriminability and bias can be selectively influenced (e.g., Snodgrass & Corwin, 1988).

Hillstrom and Logan (1997) argued that our independence assumption is not viable because the two types of processes (word reading and color naming) necessarily share some stages. However, a violation of the independence assumption produced by shared stages would not necessarily influence estimates in a way that would affect findings of process dissociations. To illustrate this, assume that W and C are interpreted as the probabilities that all stages of word reading and of color-naming processes are completed successfully⁴ (at the level of a single trial or at the level of a single cycle within a trial) and that W and C are the products of complex, multistaged processes. Adopting Hillstrom and Logan's terms, let us represent the probability of all stages of word reading processes being completed as $p(M)$, with stages x and z that are independent of each other. Furthermore, let us represent the probability of all stages of color-naming processes being completed as $p(N)$, with stages y and z that are independent of each other and independent of stage x . As Hillstrom and Logan noted,

$$W = p(M) = p(x \text{ and } z) = p(x)p(z) \quad (3)$$

and

$$C = p(N) = p(y \text{ and } z) = p(y)p(z). \quad (4)$$

Hillstrom and Logan demonstrated how such a shared stage violates stochastic independence because $p(M)p(N) < p(M \text{ and } N)$ when $1 > p(z) > 0$. Using Lindsay and Jacoby's (1994) original PD equations, we can substitute $p(x)p(z)$ for W (representing the probability of all stages of word-reading processes being completed successfully) and $p(y)p(z)$ for C (representing the probability of all stages of color-naming processes being completed successfully). The equations become

$$\begin{aligned} p(\text{correct/congruent}) \\ = p(x)p(z) + p(y)p(z) [1 - p(x)p(z)] \quad (5) \end{aligned}$$

and

$$p(\text{correct/incongruent}) = p(y)p(z) [1 - p(x)p(z)]. \quad (6)$$

Using Lindsay and Jacoby's PD procedure to extract estimates entails the use of the following two equations, which

(in this example) produce the probability of all stages of each process being completed successfully:

$$\begin{aligned} W &= p(\text{correct/congruent}) - p(\text{correct/incongruent}) \\ &= p(x)p(z) \quad (7) \end{aligned}$$

and

$$C = p(\text{correct/incongruent}) / (1 - W) = p(y)p(z). \quad (8)$$

A shared stage, such as in the example provided above, is correctly reflected in the probability of all stages of each process being completed successfully. Such a shared stage would not cause functional dependence between the parameters $p(M)$ and $p(N)$ unless $p(z)$ covaried with $p(x)$ or $p(y)$. However, in Hillstrom and Logan's example, it is explicitly stated that stages x and y are "independent of each other and independent of a shared stage, z " (p. 1566).

To produce problems for interpreting process dissociations observed with the PD estimation procedure, a violation of independence must result in correlations at the item-by-subject level. However, a violation of stochastic independence produced by an independent shared stage does not cause such a correlation. (For a discussion of possible effects of correlation at different levels, see Curran & Hintzman, 1995, 1997; Hintzman & Curran, 1997; and responses by Jacoby, Begg, & ShROUT, 1997; and Jacoby & ShROUT, 1997).

Measures, Assumptions, and Models

Lindsay and Jacoby (1994) argued that their findings indicate that neither interference nor facilitation provides an accurate measure of the influence of word-reading processes on Stroop task performance. Hillstrom and Logan (1997) protested that it is already well known that interference and facilitation do not provide accurate measures of the influence of word reading on Stroop performance, citing Jonides and Mack (1984). Jonides and Mack provided an analysis of reasons why, for example, color-naming latency for color patches may not provide an accurate measure of color-naming processes for words because of various confounding differences between color patches and words. Notwithstanding the excellent article by Jonides and Mack, the vast majority of Stroop research continues to use interference or facilitation as an index of the influence of word-reading processes (e.g., MacLeod's 1991 review of Stroop research described Stroop effects almost exclusively in terms of interference and facilitation and noted that measuring Stroop effects in terms of the difference between congruent and

⁴ It should be noted that this assumption, which treats W and C as component reliabilities, is counter to our interpretation of W and C as influences. Our treatment of W and C in this section is carried out only to illustrate that even if one assumed that W and C should be interpreted as component reliabilities, independent shared stages would not produce problems for interpreting process dissociations.

incongruent items “unfortunately combines interference and facilitation” [p. 183]).

Lindsay and Jacoby (1994) cited Jonides and Mack (1984) because one of the advantages of the PD approach is that estimates do not rely on assumptions about the process purity of control items. However, Lindsay and Jacoby emphasized a more fundamental problem: Even if one had a perfect neutral control item that accurately indexed the influence of color-naming processes in the Stroop task, if performance for incongruent items is determined by the influence of color-naming processes only to the extent that it is not influenced by word-reading processes, as described by the independence assumption, then the difference between performance for incongruent items and that for control items would not provide an accurate account of the influence of word-reading processes.

Hillstrom and Logan (1997) stated that there is little need for measures of the influence of color naming and word reading because researchers are not particularly interested in these parameter values per se but rather are interested in the processes by which the sometimes conflicting influences of color naming and word reading are resolved. In fact, however, the equations used in the PD procedure and the Stroop counter model represent a theory of how responses are selected on the basis of sometimes conflicting information. As argued by Lindsay and Jacoby (1994), the assumption that one makes about how the influences of processes are combined is important for interpreting the effects of manipulations on performance in Stroop tasks. For example, they showed that reducing the efficacy of color-naming processes by degrading color discriminability eliminated the typical asymmetry between facilitation and interference, as measured by response latency in a standard Stroop task (Experiment 1) and as measured by accuracy in a deadline Stroop task (Experiment 2).

The making of assumptions about how the information from various processes is combined is not optional if one wishes to characterize the influence of those processes on task performance. The independence assumption (that the decision-making system is influenced by one process only to the extent that it is not influenced by the other process) differs from the common assumption about the relationship between word-reading and color-naming processes, which is that the outputs from these processes are additive. Under the assumption that the outputs of word and color processes are simply additive, Lindsay and Jacoby’s (1994) findings present a curious pattern: The influence of word reading as indexed by facilitation was greater in the dull-colors condition than in the bright-colors condition, but the influence of word reading as indexed by interference was greater in the bright-colors condition than in the dull-colors condition. There is no obvious reason why manipulating the discriminability of the colors should have any effect on the influence of word reading, let alone have opposite effects on the influence of word reading as measured by facilitation as opposed to interference. Under the independence assumption, differences in performance for congruent or incongruent items versus performance for control items do not

provide good measures of the contribution of word-reading processes. When the independence assumption was made, the estimated contribution of W was shown not to be influenced by the manipulation of color.

The assumption made about the relationship between color-naming and word-reading processes in response selection defines effects to be explained. If one adopts the assumption that the contributions of the two types of processes are additive, it must be explained why manipulations of color have an impact on the estimate of word-reading processes. More generally, gaining an understanding of how the conflict between sources of influence is resolved cannot be separate from questions about the measurement of the influences of word-reading and color-naming processes.

Explaining (Away) Findings of Process Dissociations

Lindsay and Jacoby’s (1994) enthusiasm for the PD procedure was based on their findings of process dissociations and on the implications of those findings for models of performance in Stroop tasks. They did not pretend to offer a complete model of processing but rather reported regularities in results—revealed by making the combinatoric assumption of independence—that could guide the development of more complete models.

Hillstrom and Logan (1997) said that they “have frequently been challenged to explain why the results found by Lindsay and Jacoby are so consistent and interpretable given that we think the method used is flawed” (p. 1576). We do not find their answer to that challenge convincing. In large part, they responded by questioning the assumptions of the procedure and by noting that changing the assumptions changes the results. The fact that changing the assumptions has an effect is irrelevant to explaining why consistent and interpretable results are found when the assumptions of the PD procedure are made.

Seemingly, Hillstrom and Logan (1997) must claim that Stroop process dissociations are flukes of chance. Rather than reflecting contributions of independent processes, the apparent dissociations must be said to result from offsetting biases for estimates of parameters, error variance, and so forth. Lindsay and Jacoby (1994) reported three experiments with clean process dissociations, and Jacoby has obtained similar findings across a range of absolute levels of Stroop performance. Similar process dissociations also have been found in other Stroop-like tasks (Toth, Levine, Stuss, Winocur, & Meiran, 1995). In our view, the robustness of process dissociations challenges the claim that they reflect a serendipitous balance of offsetting factors.⁵

Hillstrom and Logan (1997) seem to argue that one must begin with a complete model of processing and then look for

⁵ Another reason given by Hillstrom and Logan (1997) for dismissing findings of process dissociations is that such dissociations are not always found. Certainly, there will be boundary conditions for finding dissociations, and exploring those boundary conditions will help illuminate the strengths and weaknesses of our approach.

regularities predicted by that model, rather than observing regularities in performance measured under a set of working assumptions that then inspire the development of a more complete model. The PD procedure is incomplete, it contains assumptions that have not yet been fully justified, and it certainly has boundary conditions. The same can be said for all models of Stroop performance. Although there are many questions yet to be answered, we believe that the evidence to date provides compelling support for the PD approach to Stroop phenomena; rather than dismiss the regularities that we have observed as flukes of chance, we intend to use the procedure to develop and test detailed processing models that account for those regularities.

Summary and Conclusion

We have responded to Hillstrom and Logan's (1997) central claim—that it is impossible to model Stroop phenomena with the assumptions that underlie the PD procedure—by briefly describing the Jacoby et al. (in press) Stroop counter model, which incorporates the assumptions of the PD procedure and, in the preliminary research conducted to date, accounts for both speed and accuracy in both deadline and standard Stroop tasks. Next, we offered descriptions of the parameters and assumptions of the equations used in the PD procedure and the Stroop counter model and discussed the issues of stochastic independence, functional independence, and the effects of shared stages. Finally, we discussed the measures, assumptions, and motivation for the PD procedure and the Stroop counter model. In doing so, we have provided a more elaborate description of the processing architecture in the PD procedure and the Stroop counter model.

Our interest in Stroop tasks arises in part from the importance placed on such tasks as a means of diagnosing deficits in special populations. For example, the elderly are said to suffer from greater Stroop interference than younger adults (Cohn, Dustman, & Bradford, 1984; Dulaney & Rogers, 1994; Panek, Rush, & Slade, 1984). The conclusion regarding the elderly along with nearly all of the criteria suggested by MacLeod (1991) for assessing the adequacy of Stroop models, relies on the assumption that the unintended effect of word-reading processes on Stroop performance can be validly estimated as the difference between performance for incongruent items and that for control items. We believe that this very basic assumption requires much more careful inspection of the sort that can be gained only by contrasting it with alternative assumptions. The potential gain is to redefine the constraints that must be met by an adequate theory and, in doing so, to provide a redefinition of the nature of the deficits suffered by special populations. Such a redefinition might constitute the initial step toward better diagnosis and treatment of those with a deficit in cognitive control. We hope that the continuing evolution of the PD procedure and of more detailed processing models that instantiate its assumptions will be met with the patience necessary for the development of a new approach.

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