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Issues Concerning Relative Speed of Processing Hypotheses, Schizophrenic Performance Deficits, and Prefrontal Function: Comment on Schooler et al. (1997)

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The authors have found the data presented in the C. Schooler, E. Neumann, L. J. Caplan, and B. R. Roberts (1997) article to be interesting and of potential value in constraining the further development of detailed theoretical models of Stroop performance. However, the authors have found that the relative speed of processing account of stimulus onset asynchrony (SOA) effects given by Schooler et al. in Experiment 1 fails to address several important and vexing issues faced by such accounts, which have been highlighted by existing formal models. The authors also have expressed concerns about Schooler et al.'s, interpretation of the reduction in Stroop interference observed among individuals with schizophrenia in Experiment 2. Whereas the authors have acknowledged that it is plausible to relate this to a dysfunction of prefrontal cortex, they have pointed to equally plausible alternative explanations, which are not addressed by the experiment or in the discussion in the Schooler et al. article.

Schooler, Neumann, Caplan, and Roberts (1997) have presented interesting new data regarding the performance of both normal participants and participants with schizophrenia in the Stroop task. We concur with their conclusion that these data are potentially valuable as empirical constraints on the further development of formal models of performance in this task. However, we have several concerns about the theoretical conclusions they have drawn from the results of their two experiments.

Experiment 1: Relative Speed of Processing

Schooler et al. (1997) have accounted for the stimulus onset asynchrony (SOA) effects that they have observed in this experiment in terms of the relative speed of processing of words and colors. Specifically, they have argued that the peak in interference observed at the +100-ms SOA was evidence that words are processed more rapidly than colors. This is not a new account and until recently was the dominant explanation offered for the central finding in Stroop experiments: that words interfere with colors but not the reverse. Schooler et al. have noted that this account was successfully challenged by Glaser & Glaser's (1982) study, in which it was found that presenting the color before the word has no impact on word reading. This finding has eliminated relative speed of processing as an explanation for the asymmetry of interference effects in word reading versus color naming. Nevertheless, Schooler et al. have argued that this fact does not preclude relative speed of processing as an account for the pattern of SOA effects observed in the color-naming task alone:

> We apply the relative speed hypothesis . . . only to situations that have been shown to involve two genuinely competing dimensions. . . . Because [in word reading] there is no evidence for competition between the dimensions regardless of how the order of presentation is staggered (see Glaser & Glaser, 1982), the relative speed issue does not apply. (p. 22)

We have grave concerns about this argument. At best, it dramatically restricts the scope of the account of Stroop performance given by Schooler et al. (1997) and fails to address the most puzzling and important aspect of the Stroop effect: that words can interfere with colors but not the reverse. At worst, it is ad hoc. Relative speed of processing hypotheses do not stipulate a priori that the processing of colors and words are carried out in fundamentally different ways depending upon the task (i.e., color naming vs. word reading). Therefore, to restrict the scope of the hypothesis to color naming—for which it may make the correct predictions—yet dismiss its applicability to word reading—for which it is known not to make the correct predictions—seems arbitrary if not circular. The hypothesis fails to say why relative speed applies to color naming and not word reading, when presumably many if not most of the same component processes are involved. It is in this context

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that we found our parallel distributed processing (PDP) model to be most instructive (Cohen, Dunbar, & McClelland, 1990). This asymmetry of effects could be accounted for in the PDP model without invoking any qualitative differences in the processing of colors versus words, irrespective of the task to be performed. Furthermore, the PDP model illustrates how, contrary to the assumption of Schooler et al., competition can occur, even when it is not manifest behaviorally.

Even if we accept a restriction of the relative speed of processing hypothesis to the color-naming task, there are still serious problems with this hypothesis, both empirically and theoretically. Empirically, the Glaser and Glaser (1982) study is not the only one to provide countering evidence. For example, Dunbar & MacLeod (1984) found that for the color-naming task, words still produced interference even when word processing was made to be slower than color processing (e.g., by degrading or changing the orientation of the word). MacLeod and Dunbar (1988) provided additional evidence that the degree of practice naming a particular stimulus dimension, and not its speed of processing, best predicts Stroop interference (also see Chen & Ho, 1986).

Even if these findings can be dismissed, however, it is not clear what new theoretical insights Schooler et al. (1997) have offered with a simple speed of processing account. In both existing PDP models of the Stroop effect (Cohen et al., 1990; Phaf, Van der Heuden, & Hudson, 1990), words are processed more rapidly than colors. As such, these models represent explicit implementations of relative speed of processing hypotheses. Yet, as acknowledged by all, these models fail to capture several aspects of the color-naming SOA effects. Whereas these failures may be due to idiosyncrasies of the PDP implementations, the possibility is raised by the failures of these models that there are fundamental problems with simple speed of processing accounts. These problems may be subtle, insofar as they are not apparent in verbal accounts such as the one offered by Schooler et al., but only become apparent when attempts are made to explicitly implement the mechanisms thought to be involved. The existing PDP models point to such problems. For example, if speed of processing is the only factor, why does the word not produce more interference at negative SOAs, as we have observed in the model reported in Cohen et al. (1990)? We have suggested that other factors may be involved, such as habituation or decay processes or the involvement of strategic processes that reduce the influence of the word, given enough time. However, these possibilities invoke other explanatory mechanisms, above and beyond simple speed of processing. Furthermore, if processing occurs as a "continuous and dynamic flow," as Schooler et al. have suggested (Footnote 6) and is certainly the case in the PDP models, then why are interference effects so dramatic at such a discrete point in time (the 100-ms SOA)? This discrete peak in interference has been difficult to achieve in models that implement such continuous and graded processing. Clearly, these are complex issues that demand exploration using detailed formal models. We concur that current models are incomplete and that the study presented by Schooler et al. provides valuable new data for constraining the further development of such models. However, for the very same reasons, we do not see what is added by a verbal description of their findings in terms of simple differences in the relative speed of processing. Indeed, based on the results of existing models, we consider it unlikely that relative speed of processing, on its own, is sufficient to explain the pattern of SOA effects that has been observed in this and previous studies.

Experiment 2: Schizophrenic Deficits and the Role of Prefrontal Cortex (PFC)

Schooler et al. (1997) have interpreted the results of their gap manipulation (i.e., delay between the word and color stimuli) as strong evidence that: (a) Prefrontal cortex plays a role in mediating the processing of information over very brief (300 ms) delays; (b) it does so for information that is not relevant to task-appropriate responses; and (c) individuals with schizophrenia exhibit an impairment in this function of prefrontal cortex. This is a reasonable and potentially interesting set of interpretations of their data. However, we are concerned that Schooler et al. have overlooked important features of their experimental design that may suggest alternative interpretations of schizophrenic performance in this task and of the neurobiological mechanisms involved.

Stimulus Degradation Versus Delay

The gap manipulation in Experiment 2 of Schooler et al. (1997) confounded a delay between the first and second stimuli with a substantial reduction in the duration of the first stimulus (from over 1 s to 150 ms). Even if individuals with schizophrenia have intact sensory processing, it is still possible that reducing stimulus duration could have interacted with later components of processing, which might be impaired in schizophrenia. These might include recoding from orthography to phonology, word identification, or both, which are necessary for the word to influence color naming in the Stroop task. A disturbance in such processes might be sensitive to manipulations of stimulus duration even when sensory processing is intact. The fact that individuals with schizophrenia perform normally in simple letter-identification tasks (as noted by Schooler et al.) does not address this concern. Indeed, formal models of processing in other domains have demonstrated that degrading a stimulus can elicit deficits in higher recognition processes even when performance on simpler perceptual tasks is intact (Farah, O'Reilly, & Vecera, 1993). Thus, individuals with schizophrenia may be able to accurately identify individual letters under conditions of stimulus degradation but show an impairment in word reading under identical conditions. Such a possibility is suggested by the interpretation that Schooler et al. have given of their own data from Experiment 1, which indicated a slowing of word processing for individuals with schizophrenia. This is consistent with numerous previous Stroop studies that have included a word-reading condition (e.g., Abramczyk, Jordan, & Hegel, 1983; Wapner & Krus, 1960; Wysocki & Sweet, 1985) and recent studies using simple word-pronunciation tasks (Barch et al., 1996; Vinogradov, Benioff, Ober, Shenaut, & Poole, 1995). Thus, an impairment of word reading in schizophrenia—independent of any disturbance in working memory—could produce a greater sensitivity to stimulus duration for individuals with schizophrenia than for normal participants, with briefer presentations resulting in a diminished impact of the irrelevant word on color naming. The gap manipulation in Experiment 2 of the Schooler et al. article may have unmasked such a deficit in intermediate stages of word processing rather than an inability to maintain word information over a brief delay.

Involvement of PFC

Even if it is assumed that the effects of the gap manipulation were related to the delay rather than stimulus degradation, it is not clear that these effects can confidently be attributed to prefrontal function. Delay period activity in PFC is typically elicited and considered to be behaviorally relevant when delays are greater than a second, and the stimulus is relevant to task performance. Neither was true in the Schooler et al. (1997) experiment. The authors have addressed this concern by citing recent findings that PFC cells with memory fields begin to fire immediately upon stimulus offset (Goldman-Rakic, 1987; Miller & Desimone, 1994). This suggests that PFC units may become engaged even at very brief delays. However, to our knowledge, these observations were all made when the task involved only (i.e., the animal expected) delays greater than 1 s and when the stimulus eliciting the activity was relevant to the behavioral response, as noted above. These are the conditions in which PFC is known to be behaviorally relevant (e.g., lesions interfere with performance). Thus, early PFC activity may simply reflect the fact that when PFC is involved, it is involved immediately. However, it does not establish that units in PFC are engaged when the task itself involves only brief delays or when the stimulus is irrelevant to the response. It remains to be demonstrated in neurophysiological studies that stimulus-specific activity occurs in PFC under such circumstances and that such activity is behaviorally relevant.

At the same time, it is well known that other brain regions also exhibit sustained activity, particularly for brief periods immediately following a stimulus and when no intervening stimuli are involved, which were the conditions of the Schooler et al. (1997) experiment. Indeed, one of the articles cited by Schooler et al. (Miller & Desimone, 1994) has provided an excellent example of this. It reported stimulus-specific delay period activity in inferotemporal cortex and argued that this may play an important role in short-term memory. Recent data from this group (Miller & Desimone, 1994) has suggested that at short, uninterrupted delays, these non-PFC regions may be able to support delay-period activity and mediate a contingent response independently of PFC. Thus, PFC may be most important when delays are longer, intervening stimuli are present, or both (for a discussion, see Cohen, Braver, & O'Reilly, 1996), conditions that were not tested in the current study. Furthermore, recent schizophrenia studies have pointed to the possibility that disturbances of cortical regions outside of PFC may contribute to schizophrenic cognitive deficits, including language (e.g. McCarley et al., 1993), and some have used paradigms specifically involving brief delays and no intervening stimuli (e.g. Javitt, Doneshka, Grochowski, & Ritter, 1995).

Finally, even psychologically motivated theories strongly suggest that working memory function may not be limited to PFC. Baddeley's original theory posited the involvement of slave buffer systems, responsible for the storage of information maintained in working memory. A number of neuropsychological studies motivated by this theory have suggested that these buffer systems may reside outside of PFC (for a review, see Gathercole, 1994) and that PFC plays a role in executive control, loading and coordinating the activity of these systems, but is not necessarily involved in active maintenance per se. From a different perspective, and as Schooler et al. (1997) note (Footnote 6), Anderson's ACT* theory (Anderson, 1983) defines working memory as the set of representations that have been temporarily activated within long-term memory. Of course, not all of long-term memory resides within PFC, and thus representations activated within working memory may well at times reside outside of PFC. In either case, it would seem that although the PFC may or may not be necessary for the maintenance of information in working memory, it is probably not exclusively responsible for this function. Working memory and the maintenance of information can almost certainly involve other brain regions besides PFC. This suggests that, even when a study demonstrates effects of a delay on performance (especially short delays), this cannot necessarily be assumed to reflect frontal function. Other systems that are known to exhibit delay-period activity, and that have been shown to be involved in working memory, may provide alternative loci for such effects.

We tried to make this point explicit in our theory of PFC function and its involvement in schizophrenia (Cohen & Servan-Schreiber, 1992). We specified that PFC was responsible for actively maintaining a particular type of information, which we referred to as context information. We used this to distinguish the function of PFC from other components of the system that exhibit the capacity for active maintenance. Although we accept the implication given by Schooler et al. (1997) that our definition of context may warrant further specification, we strongly favor the more restrictive of the definitions that they have discussed. That is, we consider context to refer only to information directly relevant to the selection of a task-appropriate response (for a recent extended discussion, see Cohen et al., 1996). This would exclude representations of word information in the Stroop color-naming task. Thus, on this analysis, our theory provides a more specific account of the role of PFC in active maintenance of information than other related theories. At the same time, we were careful to acknowledge that a disturbance of frontal function is likely to be just one component of the pathophysiology of schizophrenia. Our goal was to articulate a hypothesis that was sufficiently precise as to help delineate the cognitive deficits that could be ascribed to prefrontal impairment and to distinguish these from those resulting from other sources of impairment. We believe the findings reported in the Schooler et al. study provide an excellent example of how this effort has been useful. In its strong form, our hypothesis specifically predicts that the effects observed in Experiment 2 of Schooler et al. arise from a disturbance outside of PFC. The considerations discussed above are all consistent with this possibility: (a) Word processing appears to be impaired in individuals with schizophrenia; (b) the gap manipulation in Experiment 2 was confounded by reduced duration of the word stimulus (at the negative SOA), which may have interacted with a disturbance in word processing, thereby diminishing its impact on color naming; and (c) the delay introduced by the gap was very brief, it did not involve intervening distractors, and the (initial) stimulus was not relevant to the response, all of which allow that more posterior systems may have been responsible for processing during the delay, rather than frontal mechanisms.

As a final note, we would like to point out that the notion that very briefly activated representations of task-irrelevant stimuli should be considered to be part of working memory seems to stretch this construct beyond its traditional bounds. The contents of working memory are typically considered to be information that has been specifically selected for maintenance because it is relevant to the task. Indeed, in most studies that employ SOA manipulations, SOAs under approximately 500 ms are considered to tap automatic processes rather than the resource-limited, controlled processes with which working memory is typically associated.

Conclusions

In summary, we find the data presented in the Schooler et al. (1997) article to be interesting and of potential value in constraining the further development of detailed theoretical models, both of normal and schizophrenic performance in the Stroop task. However, we are less convinced by the theoretical interpretations that are offered. We find that the account of the SOA effects in the color-naming task of Experiment 1—in terms of relative speed of processing—is lacking in detail and that it fails to address several important and vexing issues faced by such accounts that have been highlighted by existing formal models. With regard to Experiment 2, we find interpretations by Schooler et al. of the effects in terms of PFC function and its role in working memory to be premature, incomplete in their consideration of alternative explanations, and possibly inconsistent with traditional concepts of working memory. We point to an equally plausible possibility that schizophrenic findings in this experiment reflect dysfunction in posterior systems, which would be consistent with the hypothesis that representations within PFC are restricted to those necessary to produce task-appropriate responses. We hope that clarification of these issues lead to follow-up empirical studies and more detailed theoretical models that address the neurobiological mechanisms underlying cognitive function, both in normal participants and in individuals with schizophrenia.

References

Abramczyk, R. R., Jordan, D. E., & Hegel, M. (1983). "Reverse" Stroop effect in the performance of schizophrenics. *Perceptual and Motor Skills, 56,* 99–106.

Anderson, J. R. (1983). *The architecture of cognition.* Cambridge, MA: Harvard University Press.

Barch, D., Cohen, J. D., Servan-Schreiber, D., Steingard, S., Steinhauer, S., & van Kammen, D. (1996). Semantic priming in schizophrenia: An examination of spreading activation using word pronunciation and multiple SOAs. *Journal of Abnormal Psychology, 105,* 592–601.

Chen, H., & Ho, C. (1986). Development of Stroop interference in Chinese–English bilinguals. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 12,* 397–401.

Cohen, J. D., Braver, T. S., & O'Reilly, R. (1996). A computational approach to prefrontal cortex, cognitive control, and schizophrenia: Recent developments and current challenges. *Philosophical Transactions of the Royal Society of London Series B, 351*(1346), 1515–1527.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review, 97,* 332–361.

Cohen, J. D., & Servan-Schreiber, D. (1992). Context, cortex, and dopamine: A connectionist approach to behavior and biology in schizophrenia. *Psychological Review, 99,* 45–77.

Dunbar, K., & MacLeod, C. M. (1984). A horse race of a different color: Stroop interference patterns with transformed words. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 622–639.

Farah, M. J., O'Reilly, R. C., & Vecera, S. P. (1993). Dissociated overt and covert recognition as an emergent property of a lesioned neural network. *Psychological Review, 100,* 571–588.

Gathercole, S. E. (1994). Neuropsychology and working memory: A review. *Neuropsychology, 8,* 494–505.

Glaser, M. O., & Glaser, W. R. (1982). Time course analysis of the Stroop phenomenon. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 875–894.

Goldman-Rakic, P. S. (1987). Circuitry of primate prefrontal cortex and regulation of behavior by representational memory. In F. Plum & V. Mountcastle (Eds.), *Handbook of Physiology—The Nervous System* (Vol. 5, pp. 373–417). Bethesda, MD: American Physiological Society.

Javitt, D. C., Doneshka, P., Grochowski, S., & Ritter, W. (1995). Impaired mismatch negativity generation reflects widespread dysfunction of working memory in schizophrenia. *Archives of General Psychiatry, 52,* 550–558.

MacLeod, C. M., & Dunbar, K. (1988). Training and Stroop-like interference: Evidence for a continuum of automaticity. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 126–135.

McCarley, R. W., Shenton, M. E., O'Donnell, B. F., Faux, S. F., Kikinis, R., Nestor, P. G., & Jolesz, F. A. (1993). Auditory P300 abnormalities and left posterior superior temporal gyrus volume reduction in schizophrenia. *Archives of General Psychiatry, 50,* 190–197.

Miller, E. K., & Desimone, R. (1994). Parallel neuronal mechanisms for short-term memory. *Science, 263,* 520–522.

Phaf, R. H., Van der Heuden, A. H. C., & Hudson, P. T. W. (1990). SLAM: A connectionist model for attention in visual selection tasks. *Cognitive Psychology, 22,* 273–341.

Schooler, C., Neumann, E., Caplan, L. J., & Roberts, B. R. (1997). A time course analysis of Stroop interference and facilitation:

Comparing normal and schizophrenic individuals. *Journal of Experimental Psychology: General, 126,* 19–36.

Vinogradov, S., Benioff, B. A., Ober, G. K., Shenaut, G. K., & Poole, J. H. (1995). Thought disorder and semantic memory information processing in schizophrenia. *Schizophrenia Research, 15*(1–2), 138.

Wapner, S., & Krus, D. M. (1960). Effects of lysergic acid diethylamide, and differences between normals and schizophrenics, on the Stroop color-word test. *Journal of Neuropsychiatry, 2,* 76–81.

Wysocki, J. J., & Sweet, J. I. (1985). Identification of brain damaged, schizophrenic, and normal medical patients using a brief neuropsychological screening battery. *An International Journal of Clinical Neuropsychology, 7*(1), 40–44.

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