

Interdimensional interference in the Stroop effect: uncovering the cognitive and neural anatomy of attention

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In the classic Stroop effect, naming the color of an incompatible color word (e.g. the word RED printed in green ink; say, 'green') is much slower and more error-prone than is naming the color of a control item (e.g. XXX or CAT printed in green; say 'green'). This seemingly simple interference phenomenon has long provided a fertile testing ground for theories of the cognitive and neural components of selective attention. We present a sketch of the behavioral phenomenon, focusing on the idea that the relative automaticity of the two dimensions determines the direction and the degree of interdimensional interference between them. We then present an outline of current parallel processing explanations that instantiate this automaticity account, and we show how existing interference data are captured by such models. We also consider how Stroop facilitation (faster response of 'red' to RED printed in red) can be understood. Along the way, we describe research on two tasks that have emerged from the basic Stroop phenomenon – negative priming and the emotional Stroop task. Finally, we provide a survey of brain imaging research, highlighting the possible roles of the anterior cingulate in maintaining attentional set and in processing conflict or competition situations.

Attention is crucial to our successful interaction with our environment, serving as the gatekeeper for the rest of cognition. Yet we recognize that attending is not easy, and that opposing forces operate on it: attention is attracted to one thing but paid to another. These functions are referred to respectively as situations where attentional control is 'exogenous' (detection driven by the world) versus 'endogenous' (concentration driven by the observer)¹. Thus, despite concentrating deeply on reading an important article, we nevertheless readily detect a knock at the office door.

This opposition – between control by the world and control by the observer – has informed our understanding of attention since the earliest psychological research. In 1886, Cattell² described some processing situations as being automatic, running off essentially without attention, whereas others demanded attention. This eventually led in the 1970s to the distinction between 'automatic' and 'controlled' processing^{3,4}, where automatic processing developed through

practice and required little attention, but controlled processing required attention to perform less-practised algorithms.

The critical balance of automaticity

Given these opposing forces, it should come as little surprise that conflict situations arise. The classic illustration is the Stroop effect⁵, named after the psychologist who created the task, John Ridley Stroop⁶. Beginning with Klein's rediscovery and extension of the effect⁷, literally thousands of studies have explored this deceptively simple yet provocative phenomenon since Stroop's original dissertation⁸. As Box 1 demonstrates, it is a compelling experience. Figure 1 shows four of the many variants of the task, and Boxes 2 and 3 outline attentional tasks deriving from the Stroop task.

The asymmetry of the interference – words interfere with color naming but colors do not interfere with word reading – suggests that reading words is more automatic (more obligatory and ballistic) than is naming colors. This

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Box 1. Experiencing the Stroop effect

1	2	3	4
red	blue	xxx	green
green	green	mmmmm	blue
yellow	red	hhhh	yellow
red	blue	sssss	green
blue	yellow	hhhh	red
green	blue	xxx	blue
blue	green	sssss	yellow
red	red	xxx	red
yellow	yellow	mmmmm	green
blue	green	sssss	red
yellow	yellow	mmmmm	blue
green	red	hhhh	yellow

Time: _____

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Fig. 1. The Stroop task.

Equipped with a stopwatch and Fig. I, you can easily replicate Stroop’s original demonstration (Ref. a). For columns 1 and 2, the task is to read each list of words aloud as fast as possible, ignoring their print color. Begin by covering all of the columns except column 1. Start the timer when you say the first word and stop it when you say the last word. Record your time. Now cover all columns except column 2 and read the words aloud again. For columns 3 and 4, the task is changed to naming the print colors aloud as fast as possible, ignoring the letters or words. Do this for the rows of colored letters in column 3 and then for the rows of colored words in column 4.

Stroop observed three primary results. First, reading words was faster than naming colors. This is consistent with word reading being more practised and hence more automatic than color naming (Refs b,c). Second, there was little difference in reading the words in columns 1 and 2 (Stroop’s Experiment

1): mismatched ink colors did not produce interference in reading the words. Third, in sharp contrast, switching from nonwords to words in color naming made a very large difference between columns 3 and 4 (Stroop’s Experiment 2): naming the colors of incompatible color words showed dramatic interference. Apparently, the greater automaticity of word reading leads to the words being read even though they should not be, producing conflicting responses to each stimulus. This both slows down color naming responses and makes errors – reading words instead of naming colors – more likely.

Modern versions of the Stroop task are typically computer-controlled displays of a single word in color, rather than multiple items on a card, permitting more control and more precise measurement of individual item and sequence effects. Also, although Stroop did not include a congruent condition (RED printed in red; say ‘red’), modern versions of the task often do. Both of these modifications were introduced by Dalrymple-Alford and Budayr (Ref. d).

References

- a Stroop, J.R. (1935) Studies of interference in serial verbal reactions. *J. Exp. Psychol.* 18, 643–662 [Reprinted in *J. Exp. Psychol. Gen.* 121, 15–23]
- b Cattell, J.M. (1886) The time it takes to see and name objects. *Mind* 11, 63–65
- c Fraisse, P. (1969) Why is naming longer than reading? *Acta Psychol.* 30, 96–103
- d Dalrymple-Alford, E.C. and Budayr, B. (1966) Examination of some aspects of the Stroop color–word test. *Percept. Mot. Skills* 23, 1211–1214

makes sense in terms of our no doubt vastly greater practice at reading. That the Stroop effect stems from differential relative automaticity is made clear in a study by MacLeod and Dunbar⁹. People were trained to respond with a particular

color name to each of four unique random polygon shapes. They were tested periodically with shapes presented in incongruent colors (e.g. the shape called ‘blue’ printed in the color green). Early in training, shape naming showed interference from incompatible print colors, but color naming was unaffected by incompatible shapes. Midway through training, each dimension interfered equivalently with the other. Finally, after extensive training, incompatible shapes interfered with color naming but incompatible colors no longer interfered with shape naming. The complete reversal of the pattern of interference clearly resulted from the shift in relative automaticity of color names and shape names with practice. Practice also has profound effects on the standard color–word Stroop effect^{5,10}.

Parallel processing supplants serial processing

Cohen *et al.*¹¹ used the MacLeod and Dunbar data as a starting point for creating a parallel distributed processing (‘connectionist’) model of performance in the Stroop task, one of the earliest and best known of such models. The architecture of the model is shown in Fig. 2. Processing occurs via activation spreading between units along pathways of different strengths. Presenting a stimulus activates input units corresponding to the word and color in the stimulus. The degree to which word reading versus color naming dominates subsequent processing is tuned by the

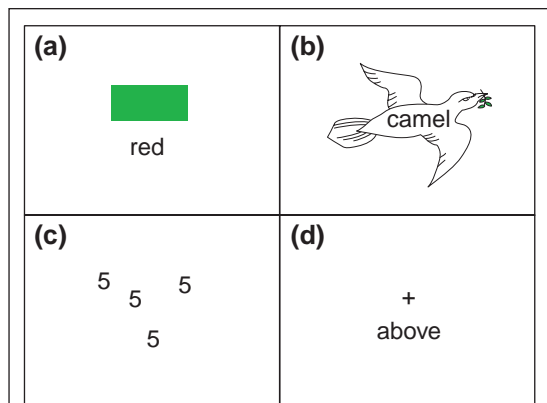


Fig. 1. Four variants of the Stroop task. (a) Separated version of the classic color–word task (name the color bar = ‘green’). (b) Picture–word (name the picture = ‘bird’). (c) Counting (count the digits = ‘four’). (d) Spatial (identify the location of the word relative to the plus = ‘below’). All panels illustrate the incongruent condition, which produces interference relative to an appropriate control.

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task demand units. Ultimately, when one of the output units crosses its threshold, a response is produced.

In this model, knowledge is realized as the pattern of activation across the units, which changes with experience over trials in a continuous, nonlinear fashion. Processing is ‘bottom up’, running strictly from input to output. Interference arises when two simultaneously active pathways produce conflicting activation at their intersection; facilitation occurs when two pathways produce coinciding activation. Such interactions can occur anywhere in the system and, indeed, at multiple locations. Attention is realized as the modulation of the operation of processing units along a pathway, so that attention is intrinsic to the model, and not an external force applied to the model.

Such models capture the idea that interference arises from the processing of the word and color in parallel^{12,13}. This interpretation contrasts with the view common until the late 1970s: the relative speed of processing, or ‘horse race’, account¹⁴. Under this account, because word processing was faster than color processing, the word response beat the color response to a limited capacity response buffer, causing interference at the response stage. If this were true, then anything that could accelerate processing of the color or decelerate processing of the word should reduce or even eliminate interference from the word onto naming of the color. Numerous results call this idea into question; we will describe only two.

First, using the separated version of the task (Fig. 1a), the word information can be presented before or after the color information. If interference in color naming results from the faster or earlier processing of the word, then presenting the color information earlier should give the color a head start, preventing the word from interfering with color naming. Indeed, when the task is word reading, if the color information leads by a long enough interval, it should be possible to obtain ‘reverse Stroop’ interference, wherein the color interferes with reading the word. However, neither of these results can be obtained, as has been shown when the stimulus onset asynchrony (temporal gap) between the word and the color was manipulated in either the color naming task or the picture naming task (Fig. 1b)^{15,16}.

Dunbar and MacLeod¹⁷ took a different tack to manipulating speed of processing. They presented standard color–word items either in normal upright orientation, where reading is well established to be faster than color naming¹⁸, or in a novel orientation (such as upside-down and backwards), where reading is known to be very slow¹⁹. Although reading the upside-down words was considerably slower than naming their print colors, the familiar pattern of Stroop interference was unaltered: even the slow-to-read rotated words produced normal interference in color naming (you can try this by turning Fig. 1 in Box 1 upside down and comparing color naming time for columns 3 and 4). Taken together with the stimulus onset asynchrony results, these findings clearly conflict with any simple relative speed of processing explanation. Thus, parallel processing accounts appear to be much more viable than serial processing accounts of the Stroop effect⁸.

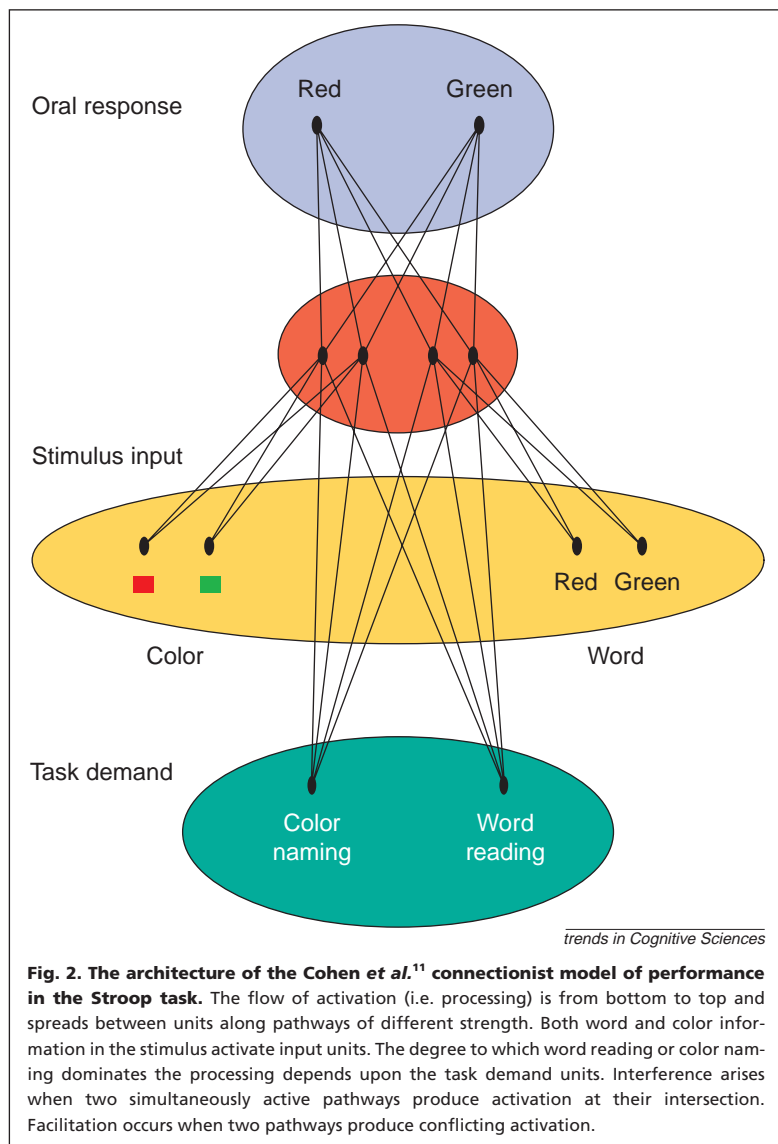


Fig. 2. The architecture of the Cohen *et al.*¹¹ connectionist model of performance in the Stroop task. The flow of activation (i.e. processing) is from bottom to top and spreads between units along pathways of different strength. Both word and color information in the stimulus activate input units. The degree to which word reading or color naming dominates the processing depends upon the task demand units. Interference arises when two simultaneously active pathways produce activation at their intersection. Facilitation occurs when two pathways produce conflicting activation.

Facilitation, the ‘flip side’ of the Stroop effect

Virtually all models of Stroop interference also predict Stroop facilitation – that responses will be faster and/or more accurate to congruent stimuli (RED printed in red; say ‘red’) than to control stimuli (e.g. XXX printed in red; say ‘red’). Indeed, faster responses are often seen in the congruent condition. But is the congruent word actually helping in the naming of the color, as the concept of facilitation suggests?

Existing accounts, including the parallel processing view, portray facilitation as the benefit of congruence, as a parallel to interference as the cost of incongruence. Yet a number of findings call such a view of facilitation into question⁸. The first hint is the always-present asymmetry of facilitation and interference effects, with facilitation being much smaller (in the order of 20 ms or less) than interference (in the order of 100 ms or more)^{10,15}. However, other results provide an even more direct challenge; we will cite just three here. Tzelgov *et al.* showed that, as the proportion of color word trials decreased (in a version of the task where color word trials and noncolor word trials were mixed), interference increased but facilitation was unaltered. They concluded that different mechanisms must be

at play in facilitation and interference²⁰. In two individual differences studies, Vanayan showed that facilitation and interference were completely uncorrelated, further supporting the implausibility of a single processing mechanism causing both facilitation and interference (M. Vanayan, PhD thesis, University of Toronto, 1992). Most recently, MacLeod has demonstrated that two of the most potent variables in cognition – amount of practice and integration versus separation of the two dimensions – both strongly affect interference but have absolutely no effect on facilitation, again suggesting a processing distinction¹⁰.

The parallel processing view that facilitation and interference are complementary results of the same processing mechanism(s) is inconsistent with these findings. We present an alternative explanation for facilitation that is consistent with the data. Consider first that congruent trials are unique because the responses to both the word and the color are identical. This creates a problem: The experimenter (perhaps the participant as well) cannot discriminate which dimension gave rise to the response on a given congruent trial. Keeping in mind the well-established finding that reading is faster than color naming^{2,18}, it is possible that undetectable reading errors will be included in the calculation of overall response times in the congruent condition, producing apparent facilitation.

This inadvertent reading hypothesis of facilitation accounts for both the inconsistency with which facilitation appears in the Stroop literature⁸ and the asymmetrical magnitude of facilitation and interference. Differing proportions of reading errors included in the calculation of congruent response times from one experiment to another and from one participant to another would produce this variability.

Direct support for the inadvertent reading hypothesis comes from the study by Dunbar and MacLeod¹⁷. By reorienting words (e.g. turning them upside-down and back-to-front) and thus reducing readability, they eliminated facilitation (relative to nonword controls)¹⁷. When reading was made sufficiently difficult that a reverse Stroop effect was obtained (incompatible colors interfering with reading the words), facilitation was absent despite the persistence of interference. When reading became slower than color naming, occasional reading errors no longer reduced average latencies in the congruent case. Indeed, reading errors may no longer even occur under these circumstances. The illusion of facilitation disappears.

We have also recently provided direct tests of this alternative explanation of facilitation (C.M. MacLeod and P.A. MacDonald 1995, Annual Meeting Psychonomic Society, Los Angeles, CA, USA; P.A. MacDonald and C.M. MacLeod 1996, Annual Meeting Psychonomic Society, Chicago, IL, USA). In these studies, bilingual subjects exhibited facilitation in the congruent condition only within language (RED printed in red; say 'red'), and in fact showed interference between languages (ROUGE printed in red; say 'red'). Similarly, for color-related words (LEMON printed in yellow; say 'yellow'), there was again interference in the congruent condition. Notice that facilitation occurred only when reading the word led to the correct response. When reading errors could be filtered, as

occurs in all other conditions except for the standard congruent condition, facilitation disappeared even though the word was conceptually identical to the color in the between-language congruent case and a strong associate of the color in the color-related congruent case. Perhaps most tellingly, a manipulation that promoted reading errors (visible only in the incongruent condition), increased facilitation substantially. This is especially impressive given the numerous manipulations that have failed to affect facilitation^{10,20}. Facilitation is enhanced when average latencies in the congruent condition include greater numbers of reading response times, which substitute undetectably for correct color naming response times. If apparent facilitation really is due to accidental reading, this poses a challenge to theories that predict true conceptual facilitation as a corollary of interference.

Localization of the Stroop effect by brain-imaging studies

Investigation of the neural correlates of Stroop performance has become a major research focus with the advent of functional neuroimaging techniques to explore the brain regions that govern attention in normal individuals and in clinical patients (see Box 2). Early studies used ERPs (Refs 21,22). However, we will focus on more recent studies using PET (Refs 23–26) and fMRI (Refs 27,28) where investigators have compared regional cerebral blood flow for performance in the incongruent condition with that in various control conditions (i.e. colored crosses²³, congruent words^{23,26}, neutral words^{24,27}, mixed congruent and neutral words²⁴, or colored hash marks²⁵). With two exceptions^{24,28}, all investigations have involved contrasting blocks of all-incongruent, all-control, and/or all-congruent trials in the color-word or the counting (Fig. 1c)²⁷ Stroop tasks. Although this trial-type blocking can be problematic, particularly in the congruent case where participants can simply adopt the strategy of reading the words, findings appear to converge across these studies.

In all but two experiments^{23,25} maximal differential activation for the comparison of the incongruent and control conditions occurred in the anterior cingulate^{23,24,26–29}. Other structures that consistently showed differential increases in activation for the incongruent case were the frontal polar cortex^{23,24}, inferior temporal gyrus^{24,27}, and superior²⁷ and inferior^{24,25} parietal lobule. It appears that the anterior cingulate mediates processes involved in Stroop interference, given the relatively consistent observation that it shows greatest activation in the incongruent condition of the task, as shown in the fMRI image in Figure 3. However, whether the precise role of the anterior cingulate is the application of attentional control or the detection of informational conflict has been a matter of considerable debate. Bush *et al.*³⁰ have provided a very recent summary of the work on the role of the anterior cingulate in attention, including studies of Stroop interference.

In light of other results linking anterior cingulate with divided attention³¹ and with response selection/generation³², most Stroop investigators concur that the anterior cingulate is probably involved in task-relevant control of attention and/or response selection in the presence of conflicting information or competing sources of information,

Box 2. Clinical investigations using the Stroop effect

Increased interest in the Stroop task was stimulated among clinical investigators by evidence that: (1) Stroop performance is impaired by lesions in the prefrontal cortex (Ref. a; but see also J.V. Baldo and A.P. Shimamura 1995, Annual Meeting Cognitive Neuroscience Society, San Francisco, CA, USA); (2) Stroop interference is related to increased activation of anterior cingulate cortex (Ref. b); and (3) several patient groups reveal an enhanced Stroop effect relative to nonpatient controls, including schizophrenic and manic patients (Ref. c) and the elderly with memory impairments (Refs d,e). Consequently, the Stroop task is now commonly used as an index of attentional deficits, and is routinely included in neuropsychological test batteries serving as a non-invasive means for investigating the integrity of the frontal lobes and associated structures (e.g. Ref. d).

The Stroop task has also been used as an implicit measure of word processing in aphasics (Ref. f), neglect dyslexics (Ref. g), and patients with Balint's syndrome (Ref. h). To make the link between suspected neurophysiological abnormality and observed attentional deficits more explicit, Carter *et al.* (Ref. i) used PET to show that, for schizophrenics, greater Stroop interference was related to reduced activation of the anterior cingulate (but see also Ref. j).

Modifications of the Stroop task have also been used to investigate attentional biases thought to underlie affective disorders such as depression, anxiety, and anorexia. In these 'emotional Stroop' tasks, color words are replaced with emotion-inducing words (e.g. DEATH) or disorder-related words (e.g. MISERY for depressed patients; CRAWLY for spider phobics; FAT for anorexics). Patients generally demonstrate increased interference when color-naming such emotional, disorder-specific Stroop items (for a review, see Ref. k). This has been interpreted as showing that attentional biases play a role in the development and maintenance of affective disorders. The emotional Stroop task also potentially provides a means to test recovery from emotional disturbance (Ref. k).

A recent fMRI study investigated the emotional counting Stroop task in non-patient participants (Ref. l; see also Ref. m). Although latencies did not differ for counting negatively valenced words relative to neutral words, greater activation occurred for negative words in the affective division of the anterior cingulate (i.e. the rostral-ventral region). This contrasts with the activation seen in the standard, non-emotional counting

Stroop task (Ref. n), which is primarily in the cognitive division of the anterior cingulate (i.e. the dorsal region). Future studies will undoubtedly combine brain imaging techniques and Stroop tasks to gain greater insight into neurophysiological processing differences between patients and control participants.

References

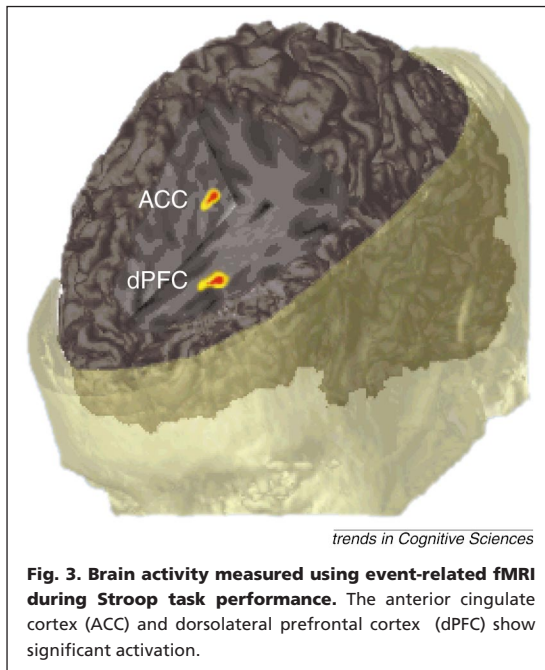
- a Perret, E. (1974) The left frontal lobe of man and the suppression of habitual responses in verbal categorical behavior. *Neuropsychologia* 12, 323–330
- b Pardo, J.V. *et al.* (1990) The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. *Proc. Natl. Acad. Sci. U. S. A.* 87, 256–259
- c McGrath, J. *et al.* (1997) Performance on tests sensitive to impaired executive ability in schizophrenia, mania, and well controls: acute and subacute phases. *Schizophr. Res.* 26, 127–137
- d Hanninen, T. *et al.* (1997) Decline of frontal lobe functions in subjects with age-associated memory impairment. *Neurology* 149, 148–153
- e Fisher, L.M. *et al.* (1990) Stroop color-word test performance in patients with Alzheimer's disease. *J. Clin. Exp. Neuropsychol.* 12, 745–758
- f Revonsuo, A. (1995) Words interact with colors in a globally aphasic patient: evidence from a Stroop-like task. *Cortex* 31, 377–386
- g Berti, A. *et al.* (1994) Nonconscious reading? Evidence from neglect dyslexia. *Cortex* 30, 181–197
- h Wojciulik, E. and Kanwisher, N. (1998) Implicit but not explicit binding in a Balint's patient. *Vis. Cognit.* 5, 157–181
- i Carter, C.S. *et al.* (1997) Anterior cingulate gyrus dysfunction and selective attention deficits in schizophrenia: H₂¹⁵O PET study during single-trial Stroop task performance. *Am. J. Psychiatry* 154, 1670–1675
- j Nordahl, T.E. *et al.* (1996) Temporal lobe metabolic differences in medication-free outpatients with schizophrenia via the PET-600. *Ital. J. Neurolog. Sci.* 16, 341–376
- k Williams, J.M.G. *et al.* (1996) The emotional Stroop task and psychopathology. *Psychol. Bull.* 120, 3–24
- l Whalen, P.J. *et al.* (1998) The emotional counting Stroop paradigm: a functional magnetic resonance imaging probe of anterior cingulate affective division. *Biol. Psychiatry* 44, 1219–1228
- m George, M.S. *et al.* (1994) Regional brain activity when selecting a response despite interference: an H₂¹⁵O PET study of the Stroop and an emotional Stroop. *Hum. Brain Mapp.* 1, 194–209
- n Bush, G. *et al.* (1998) The counting Stroop: an interference task specialized for functional neuroimaging – validation study with functional MRI. *Hum. Brain Mapp.* 6, 270–282

as in the incongruent condition^{23,24,26,27}. A finding that constrains this interpretation, though, is that the congruent condition has thus far yielded increased activation of the anterior cingulate relative to a control condition in all cases where this comparison could be made^{23,24}.

In the congruent case, the two sources of information agree, so no response conflict or conceptual discrepancy occurs from the competing word and color dimensions. This is not the case for the neutral-word control condition (e.g. CAT printed in red; say 'red') where two distinct, conceptually discrepant responses are available (although one is irrelevant to color naming). Nevertheless, anterior cingulate involvement is greater in the congruent condition than in the control condition. To accommodate this, it could be argued that in the congruent case conflict does arise in deciding which dimension (color or word) should be attended to

and should govern responding. Given that both dimensions belong to the response set in the congruent case, they should compete for attention more strongly than in the control condition. The most plausible explanation for these Stroop findings is that the anterior cingulate discriminates between sources of information, directing attention to the appropriate source, regardless of conflicting information or response tendencies. In essence, the function of the anterior cingulate in the Stroop task may be to maintain the goal of attending to and responding to color.

Maintaining goal-oriented processing might additionally involve gating task-irrelevant information, which would also fit with the clinical evidence in Box 2. Findings in the Stroop task that increased activation in the anterior cingulate is accompanied by decreased activation in other regions (i.e. the posterior cingulate, superior temporal



cortexes, parietal association cortex, and striate and left extrastriate cortex) have been interpreted as evidence that the anterior cingulate performs this gating function as well^{23,24}. Specifically, these decreases have been posited to reflect inhibition of cortical regions involved in word representation²³.

A comprehensive theory of anterior cingulate function has not yet been put forward. However, this proposed role of the anterior cingulate in the Stroop task is not at odds with conclusions drawn from other literatures³⁰. The view that the anterior cingulate performs an executive function in directing attention to a goal, even in the absence of conflicting information, is additionally bolstered by findings of increased anterior cingulate activation in anticipation of a task^{33,34}. Not surprisingly, the anterior cingulate has also been implicated in other related processes, such as error detection and monitoring, working memory, and conflict or competition monitoring³⁰.

Although this explains the greater activation of the anterior cingulate in the congruent and incongruent conditions relative to the neutral condition, it introduces two new puzzles. First, why does the pattern of activation of the anterior cingulate not correspond to the response time ordering of the conditions? That is, why is the anterior cingulate most active in the incongruent condition, less active in the congruent condition, and least active in the control condition when, in contrast, response times are longest in the incongruent condition, intermediate in the control condition, and shortest in the congruent condition? Second, why is there differential anterior cingulate activation between the congruent and incongruent conditions? It would seem that the competition between word and color should be at least equivalent in the two cases. In fact, one might expect greater difficulty discriminating the source of a response in the congruent case. The next finding might provide some insight.

Increases in activation in the lingual gyrus correlate with attending to color^{35,36}. Yet independent investigations

have found decreased activation in the lingual gyrus in the congruent condition relative to the control and incongruent conditions^{24,26}. These findings suggest that participants may perform congruent trials differently from other trials, more often failing to maintain task-relevant color processing²⁴. If so, then reduced anterior cingulate involvement in the congruent condition relative to the incongruent condition could reflect the application of a more lax criterion for ensuring that the appropriate but less automatic color dimension determines responding when both the word and the color yield the correct response. Intriguingly, these neuroimaging studies provide no evidence of a true enhancement of color processing by the congruent word (i.e. conceptual facilitation). If anything, they suggest greater difficulty in processing congruent items than in processing control stimuli. Thus, these findings are consistent with our inadvertent reading hypothesis of facilitation (C.M. MacLeod and P.A. MacDonald 1995, Annual Meeting Psychonomic Society, Los Angeles, CA, USA; P.A. MacDonald and C.M. MacLeod 1996, Annual Meeting Psychonomic Society, Chicago, IL, USA).

In contrast to this view that anterior cingulate acts to maintain the goal set in the Stroop task, the results of a recent study by Carter *et al.* appear to support a conflict detection role²⁸. Using event-related fMRI, they compared performance in a block of 80% incongruent and 20% congruent Stroop trials to performance in a block of 80% congruent and 20% incongruent Stroop trials. The intent was to differentiate the function of maintaining attention to the appropriate dimension from that of evaluating conflict. For the incongruent trials in the 80% incongruent case, conflict was considered low and the need for strategic control of attention to color was high. For the incongruent trials in the 20% incongruent block, conflict was deemed high and goal-directed control of attention was considered low because these occasional incongruent trials were embedded in many congruent trials where responding to either the word or the color would yield a correct response. Anterior cingulate activation increased only for correctly performed incongruent trials in the 20% incongruent block relative to the other conditions, leading the authors to conclude that the anterior cingulate responds to high conflict and is involved in evaluating that conflict rather than in the strategic control of attention.

An aspect of Carter *et al.*'s results leads us to question the assumptions on which their conclusions are based. The behavioral signature of having achieved low goal-directed control of attention for the 20% incongruent trials would be a significant increase in errors (i.e. more responses to the word dimension) in this condition. That is, if the lax selection criterion (or low control) that purportedly characterizes performance on congruent trials generalized to the incongruent trials in this block (as was the aim), reading error rates should be considerably inflated. However, the errors for the incongruent trials were in fact equivalent in the 20% and 80% incongruent conditions. This suggests modulation of goal-directed control of attention across conditions within as well as between blocks, compromising Carter *et al.*'s straightforward interpretation.

This design has been conceptually replicated in the Eriksen flanker task by Botvinick *et al.*³⁷, the intent again

Box 3. The origin of negative priming

While examining the effect of stimulus sequencing on Stroop interference, Dalrymple-Alford and Budayr (Ref. a) discovered a greater delay and an increased error rate when an item appeared in the color that had been the ignored word for the previous stimulus (e.g. GREEN printed in red; say 'red', followed by YELLOW printed in green; say 'green'). They attributed this increased interference to the suppression of the word during naming of the color, resulting in 'temporary unavailability of that response' (p. 1214). The phenomenon is now called 'negative priming'.

Try this yourself. Return to Fig. 1 in Box 1 and name the colors of the words in columns 2 and 4, timing each column separately. You should take longer for column 2, which is made up entirely of negative priming sequences, than for column 4, which contains no negative priming sequences.

Negative priming has since been studied widely (Refs b,c), and has been more generally defined as a longer delay and/or an increase in errors when responding to a recently ignored item. The phenomenon has been instrumental in bolstering the dual-process view of selective attention (Ref. d), whereby relevant information is highlighted and irrelevant information is actively blocked. It has also played a leading role in furthering the concept of cognitive inhibition, now widely used as an explanatory construct in studies of attention and memory (Ref. e).

Despite the early predominance of the inhibition explanation (Ref. f), alternative accounts have been proposed (Refs g–i). Challenging the idea of inhibition in negative priming, recent findings suggest that negative priming does not result from previously ignoring a stimulus (Refs j,k); rather, it is the consequence of processing mismatches across successive presentations of the repeated item (Refs i,l–n), thereby supporting memory-based accounts (Refs g,o).

The negative priming paradigm, born of the Stroop task, has also proved to be a valuable tool for studying attention and memory, and especially the interplay between them. Indeed, other attentional tasks – such as the flanker task (Ref. p) and the global–local task (Ref. q) – also owe a considerable debt to the Stroop task.

References

- a Dalrymple-Alford, E.C. and Budayr, B. (1966) Examination of some aspects of the Stroop colour-word test. *Percept. Mot. Skills* 23, 1211–1214
- b Fox, E. (1995) Negative priming from ignored distractors in visual selection: a review. *Psychonomic Bull. Rev.* 2, 145–173
- c May, C.P. et al. (1995) Determinants of negative priming. *Psychol. Bull.* 118, 35–54
- d Desimone, R. and Duncan, J. (1995) Neural mechanisms of selective visual attention. *Annu. Rev. Neurosci.* 18, 193–222
- e Milliken, B. and Tipper, S.P. (1998) Attention and inhibition. In *Attention* (Pashler, H., ed.), pp. 191–218, Psychology Press
- f Tipper, S.P. (1985) The negative priming effect: inhibitory priming by ignored objects. *Q. J. Exp. Psychol.* 37A, 571–590
- g Lowe, D.G. (1979) Strategies, context, and the mechanism of response inhibition. *Mem. Cognit.* 7, 382–389
- h Neill, W.T. and Valdes, L.A. (1992) Persistence of negative priming: steady state or decay? *J. Exp. Psychol. Learn. Mem. Cognit.* 18, 565–576
- i Park, J. and Kanwisher, N. (1994) Negative priming for spatial location: identity mismatching, not distractor inhibition. *J. Exp. Psychol. Hum. Percept. Perform.* 20, 613–623
- j MacDonald, P.A. et al. (1999) Negative priming effects that are bigger than a breadbox: attention to distractors does not eliminate negative priming but rather enhances it. *Mem. Cognit.* 27, 197–207
- k Wood, T. and Milliken, B. (1998) Negative priming without ignoring. *Psychonomic Bull. Rev.* 5, 470–475
- l Chiappe, D.L. and MacLeod, C.M. (1995) Negative priming is not task bound: a consistent pattern across naming and categorization tasks. *Psychonomic Bull. Rev.* 2, 364–369
- m MacLeod, C.M. et al. The crucial roles of stimulus identity and stimulus matching in negative priming. *Psychonomic Bull. Rev.* (in press)
- n MacDonald, P.A. and Joordens, S. (2000) Investigating a memory-based account of negative priming: support for selection-feature mismatch. *J. Exp. Psychol. Hum. Percept. Perform.* 26, 1478–1496
- o Neill, W.T. and Mathis, K.M. (1998) Transfer-inappropriate processing: negative priming and related phenomena. In *The Psychology of Learning and Motivation*, (Vol. 38) (Medin, D.L., ed.), pp. 1–23, Academic Press
- p Eriksen, B.A. and Eriksen, C.W. (1974) Effects of noise letters upon the identification of a target letter in a nonsearch task. *Percept. Psychophys.* 16, 143–149
- q Navon, D. (1977) Forest before trees: the precedence of global features in visual perception. *Cognit. Psychol.* 9, 353–383

being to contrast event-related fMRI signals for performance on trials deemed to be low conflict/high attentional control versus high conflict/low attentional control. In the former condition, an incompatible trial followed another incompatible trial; in the latter condition, an incompatible trial followed a compatible trial. As in the Carter *et al.* study²⁸, anterior cingulate activation was maximal in the high conflict/low attentional control condition but increased error rates – the hallmark of low attentional control in the face of high conflict – failed to appear in the low attentional control condition.

It is possible that the greater anterior cingulate activation for the incongruent trials in the 20% incongruent condition²⁸, and for the incompatible flanker trials that followed compatible flanker trials³⁷, reflects greater strategic control in these conditions to overcome the increased conflict. This fits with the very low and equivalent error rates across conditions. Upon encountering the occasional incongruent trial in the mostly congruent block, or an

incompatible trial following a compatible trial in the flanker task, conflict would indeed be very high at the outset. This would require greater goal-directed attention to avoid making errors. The fact that participants infrequently generated erroneous responses in these conditions suggests a dynamic and strategic regulation of attention on a trial-by-trial basis. Clinical findings (see Box 2) can also be seen as consistent with this account.

A significant challenge to the conclusion that the function of the anterior cingulate in the Stroop task is the evaluation of conflict comes from the observation that anterior cingulate activation is greater in the congruent condition than in the control condition^{22,23}. Yet in the congruent case the word and the color dimensions agree and hence there is no conflict, whereas in the control condition the word and the color are conceptually discrepant so there is conflict.

Despite some controversy at this early stage, application of neuroimaging techniques to the study of processing in the Stroop task has supported the prevalent view that the

anterior cingulate is intimately involved in aspects of selective attention. Nevertheless, current neuroimaging studies do not provide evidence that differentiates theories of Stroop interference. Rather, the functions attributed to the anterior cingulate figure into all prevalent explanations of Stroop interference. The relative speed of processing, automaticity of reading, and parallel distributed processing accounts all require: (1) maintenance of goal-oriented processing and (2) blocking of more readily available word-reading responses. Problems associated with imaging techniques (such as condition blocking), and with the application of these techniques to the study of millisecond effects, limit inferences about Stroop interference derived from current studies. Although the slowness of the haemodynamic response will be a difficult stumbling block to overcome in PET and fMRI investigations of such rapid effects, to their credit, Carter and colleagues are making strides in the neurocognitive study of Stroop by cleverly avoiding fully blocked conditions, as well as by, most recently, applying the event-related fMRI approach. As an indication of the promise of these techniques, the current cognitive neuroscience findings do seem to offer intriguing insights into the processes that might underlie facilitation in the Stroop task.

Conclusions

We had four goals in this brief review article: (1) to characterize one of the most robust and well-known phenomena in attention; (2) to illustrate the theoretical explanations of the phenomenon at the behavioral level; (3) to describe some of the new tasks and research directions that have grown out of the Stroop task; and (4) to depict how recent cognitive neuroscience techniques have begun to elucidate the brain regions involved in performing the task. Interference reflects upon our ability to choose successfully what we wish to analyze in our environment and to ignore what we should disregard. The Stroop effect demonstrates that we cannot screen perfectly for what is relevant and that, indeed, we process simultaneously more than what is necessary, sometimes to our detriment (see Lavie and Cox³⁸ for an intriguing recent perspective on when we are most likely to experience interference). Additionally,

investigations of the Stroop task are proving to be informative about the brain structures underlying our fundamental cognitive operations.

The Stroop effect has for 65 years withstood the test of time, fascinating a succession of psychologists, cognitive scientists, and cognitive neuroscientists. Studies of this color–word interference effect have helped us to understand that attention is, fundamentally, a matter of the control and direction of cognitive processing, which is most visible in situations of conflict. As such, we can think of attention as the ‘front end’ of cognition, the first step in the selection of the dimension(s) to which we will devote our processing. What could seem like an intellectual curiosity lying outside the realm of normal cognition instead has turned out to be a powerful tool for understanding the fundamental operations of mind.

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References

- 1 Posner, M.I. (1980) *Attention and Consciousness*, Lawrence Erlbaum Associates
- 2 Cattell, J.M. (1886) The time it takes to see and name objects. *Mind* 11, 63–65
- 3 Posner, M.I. and Snyder, C.R.R. (1975) Attention and cognitive control. In *Information Processing and Cognition: The Loyola Symposium* (Solso, R.L., ed.), pp. 55–85, Lawrence Erlbaum Associates
- 4 Shiffrin, R.M. and Schneider, W. (1977) Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychol. Rev.* 84, 127–190
- 5 Stroop, J.R. (1935) Studies of interference in serial verbal reactions. *J. Exp. Psychol.* 18, 643–662 [Reprinted in *J. Exp. Psychol. Gen.* 121, 15–23]
- 6 MacLeod, C.M. (1991) John Ridley Stroop: creator of a landmark cognitive task. *Can. J. Psychol.* 32, 521–524
- 7 Klein, G.S. (1964) Semantic power measured through the interference of words with color-naming. *Am. J. Psychol.* 77, 576–588
- 8 MacLeod, C.M. (1991) Half a century of research on the Stroop effect: an integrative review. *Psychol. Bull.* 109, 163–203
- 9 MacLeod, C.M. and Dunbar, K. (1988) Training and Stroop-like interference: evidence for a continuum of automaticity. *J. Exp. Psychol. Learn. Mem. Cognit.* 10, 304–315
- 10 MacLeod, C.M. (1998) Training on integrated versus separated Stroop tasks: the progression of interference and facilitation. *Mem. Cognit.* 26, 201–211
- 11 Cohen, J.D. et al. (1990) On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychol. Rev.* 97, 332–361
- 12 Phaf, R.H. et al. (1990) SLAM: a connectionist model for attention in visual selection tasks. *Cognit. Psychol.* 22, 273–341
- 13 Logan, G.D. (1980) Attention and automaticity in Stroop and priming tasks: theory and data. *Cognit. Psychol.* 12, 523–553
- 14 Dyer, F.N. (1973) The Stroop phenomenon and its use in the study of perceptual, cognitive, and response processes. *Mem. Cognit.* 1, 106–120
- 15 Glaser, M.O. and Glaser, W.R. (1982) Time course analysis of the Stroop phenomenon. *J. Exp. Psychol. Hum. Percept. Perform.* 8, 875–894
- 16 Glaser, W.R. and Dünghoff, F.-J. (1984) The time course of picture-word interference. *J. Exp. Psychol. Hum. Percept. Perform.* 10, 640–654

Outstanding questions

- How does the priority for automatic processing of a dimension develop with experience? Under what conditions can this priority be overridden?
- For multidimensional stimuli, does facilitation of the target dimension arise from the same mechanism(s) as interference? Are there common mechanisms (and common brain regions) across different tasks that display facilitation and interference?
- Does attentional interference rely, in whole or in part, on a process of cognitive inhibition? How can inhibition be discriminated from response competition?
- Do the standard Stroop task and the emotional Stroop task rely on distinct brain regions? If so, does this map onto the cognitive–emotional distinction between the dorsal division and the rostral–ventral division of the anterior cingulate cortex?
- What brain structures are responsible for maintaining task set, as opposed to detecting or resolving (potential) interdimensional conflict? Is the anterior cingulate involved in both of these attentional functions?

- 17 Dunbar, K.N. and MacLeod, C.M. (1984) A horse race of a different color: Stroop interference patterns with transformed words. *J. Exp. Psychol. Hum. Percept. Perform.* 10, 622–639
- 18 Fraisse, P. (1969) Why is naming longer than reading? *Acta Psychol.* 30, 96–103
- 19 Kolers, P.A. (1975) Memorial consequences of automatized encoding. *J. Exp. Psychol. Hum. Learn. Mem.* 1, 689–701
- 20 Tzelgov, J. et al. (1992) Controlling Stroop effects by manipulating expectations for color words. *Mem. Cognit.* 20, 727–735
- 21 Duncan-Johnson, C.C. (1981) P300 latency: a new metric of information processing. *Psychophysiology* 18, 207–215
- 22 Duncan-Johnson, C.C. and Kopell, B.S. (1981) The Stroop effect: brain potentials localize the source of interference. *Science* 214, 938–940
- 23 Bench, C.J. et al. (1993) Investigations of the functional anatomy of attention using the Stroop test. *Neuropsychologia* 32, 907–922
- 24 Carter, C.S. et al. (1995) Interference and facilitation effects during selective attention: an H₂¹⁵O PET study of Stroop task performance. *Neuroimage* 2, 264–272
- 25 George, M.S.E.C. et al. (1994) Regional brain activity when selecting a response despite interference: an H₂¹⁵O PET study of the Stroop and an emotional Stroop. *Hum. Brain Mapp.* 1, 194–209
- 26 Pardo, J.V. et al. (1990) The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. *Proc. Natl. Acad. Sci. U. S. A.* 87, 256–259
- 27 Bush, G. et al. (1998) The counting Stroop: an interference task specialized for functional neuroimaging – validation study with functional MRI. *Hum. Brain Mapp.* 6, 270–282
- 28 Carter, C.S. et al. (2000) Parsing executive processes: strategic versus evaluative functions of the anterior cingulate cortex. *Proc. Natl. Acad. Sci. U. S. A.* 97, 1944–1948
- 29 Derbyshire, S.W.G. et al. (1998) Pain and Stroop interference activate separate processing modules in anterior cingulate. *Exp. Brain Res.* 118, 52–60
- 30 Bush, G. et al. (2000) Cognitive and emotional influences in anterior cingulate cortex. *Trends Cognit. Sci.* 4, 215–222
- 31 Corbetta, M. et al. (1991) Selective and divided attention during visual discriminations of shape, color, and speed: functional anatomy by positron emission tomography. *J. Neurosci.* 11, 2383–2402
- 32 Petersen, S.E. et al. (1988) Positron emission tomographic studies of the cortical anatomy of single-word processing. *Nature* 331, 585–589
- 33 Murtha, S. et al. (1996) Anticipation causes increased blood flow to the anterior cingulate cortex. *Hum. Brain Mapp.* 4, 103–112
- 34 Ploghaus, A. et al. (1999) Dissociating pain from its anticipation in the human brain. *Science* 284, 1979–1981
- 35 Corbetta, M. et al. (1990) Attentional modulation of neural processing of shape, color, and velocity in humans. *Science* 248, 1556–1559
- 36 Luecke, C.J. et al. (1989) The color center on the cerebral cortex of man. *Nature* 340, 386–389
- 37 Botvinick, M. et al. (1999) Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature* 402, 179–181
- 38 Lavie, N. and Cox, S. (1997) On the efficiency of visual selective attention: efficient visual search leads to inefficient distractor rejection. *Psychol. Sci.* 8, 395–398

Escape from illusion: reducing false memories

Chad S. Dodson, Wilma Koutstaal and Daniel L. Schacter

Illusory memories are unsettling, but far from uncommon. Over the past several years, increasing experimental and theoretical attention has focused on misattribution errors that occur when some form of memory is present but attributed to an incorrect time, place or source. Demonstrations of errors and distortions in remembering raise a question with important theoretical and practical implications: how can memory misattributions be reduced or avoided? We consider evidence that documents the occurrence of illusory memories, particularly false recognition responses, and then review three ways in which memory distortion can be minimized.

Although memory is generally accurate, some illusions and distortions in remembering are almost unavoidable. People might accept illusory memories as true without questioning them unless (or until) they encounter contradictory evidence. Recalling his experience with the Vietnam War draft, Garry Trudeau provides an example of the durability of false memories¹. Trudeau distinctly remembers calls of concern that he received from family and friends when they learned of his draft number. He accepted the validity of this memory for several years until he spoke with those whom he believed had commiserated with him and

discovered that none of them remembered calling him. Trudeau now believes that he only imagined their concerns. In the course of examining this recollection more closely, he eventually concluded that he was, in fact, out having a few beers that night.

Memory distortions and illusions are troubling because they raise doubts about whether memory is a faithful mirror of the past. More practically, the prevalence and power of memory distortions raise an important question: how can false memories be reduced or even eliminated? We will first focus on two types of memory distortion, known as

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