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Attention: Beyond Stroop's (1935) colour–word interference phenomenon

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BACKGROUND TO THE CLASSIC STUDY

At the dawn of experimental psychology, conducting his dissertation research under Wilhelm Wundt, James McKeen Cattell demonstrated that words were faster to read than objects or colours were to name, concluding that 'This is because, in the case of words and letters, the association between the idea and name has taken place so often that the process has become automatic, whereas in the case of colours and pictures we must by a voluntary effort choose the name' (Cattell, 1886, p. 65). Thus was born the modern concept of automaticity, so influential today in our thinking about cognitive processing (see Moors & De Houwer, 2006, for a review). Of course, the idea of automaticity of behaviour has a much longer history: it is evident in the writings of the Greek philosophers, as in Aristotle's analysis of virtue.

Over the next 50 years, researchers tested the idea of differential practice as the mechanism underlying Cattell's finding, usually contrasting it with the principal alternative – differential interference or competition – that 'One particular response habit has become associated with each word while in the case of colours themselves a variety of response tendencies have developed' (Peterson, Lanier, & Walker, 1925, p. 281). This alternative, first expressed by Woodworth and Wells (1911), was championed by Joseph Peterson but 50 years passed from the time of Cattell's report until one of Peterson's students combined the two dimensions – word and colour – into a single task. The result was to become the best known phenomenon in all of psychology – the Stroop effect (see MacLeod, 1991a, for more background).

DETAILED DESCRIPTION OF THE CLASSIC STUDY

In his dissertation research, John Ridley Stroop set out to explore the phenomenon of interference (for a biographical sketch of Stroop, see MacLeod, 1991b).

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Until that time, interference had most often been studied in the context of memory, where previously learned information sometimes disrupted remembering or new learning. Stroop (1935) wanted to study what we would now call 'on-line' processing. He set out to do so by examining interference, where one dimension of a stimulus competed with another simultaneously displayed dimension, more in keeping today with the study of attention than with the study of memory. He had been exploring word reading and colour naming with Peterson, and his simple but powerful insight was to print words in colour, and then to pit the two dimensions against each other.

Although the essence of Stroop's study is widely known, exactly what he did is often incorrectly reported, so it is worthwhile to précis his study. He set out to answer two questions: what effect each dimension of a compound stimulus has on responding to the other dimension (Experiments 1 and 2), and what effect practice has on the interaction of dimensions (Experiment 3). I will omit discussion of his considerably more complicated Experiment 3 concerned with practice, emphasising the first two experiments that set out the famous phenomenon that now bears his name.

In Experiment 1, he measured the effect of incongruent ink colours on the task of reading words aloud (e.g., for the word RED printed in green ink, the correct response would be 'red'). He used five words and their corresponding ink colours: red, blue, green, brown, and purple. In the experimental condition, each word appeared equally often in each of the other four ink colours on one 10 × 10 stimulus card; the stimuli appeared in reverse order on a second card. The control cards were each identical to an experimental card but all of the words were printed in black ink only. Subjects were to read the words aloud as quickly as possible, correcting errors as they read. The data from the 70 subjects tested in Experiment 1 are shown in the top row of Table 6.1. Although subjects averaged 2.3 seconds longer to read the 100 words on the experimental cards, this 5.6% increase was far from significant.

In Experiment 2, the task was naming the colours aloud (e.g., in the above example, saying 'green'). The control cards substituted solid colour squares for the coloured words. The experimental cards and the procedure were otherwise identical to those of Experiment 1, the critical change being the switch from word reading to colour naming. The data from the 100 subjects tested in Experiment 2 are shown in the bottom row of Table 6.1. Subjects averaged 47 seconds longer to name the ink colours of the incongruent words than of the colour squares, a highly significant 74% increase. A replication almost 60 years later (MacLeod, 1991a) produced results almost identical to Stroop's.

Stroop's study is often described in textbooks and article introductions as if there was a single experiment examining colour naming – or a single experiment contrasting word reading and colour naming – but he actually carried out two separate experiments. Quite often, his word-reading findings (Experiment 1) are not even mentioned. Most egregious, perhaps, is that he is sometimes credited with including a congruent condition (e.g., the word RED in red, say 'red'), which he did not do, likely because he realised that subjects would 'cheat' and simply read the words even if they were instructed to name the colours, given that the responses would be the same in the two cases. The congruent condition had to

Table 6.1 The data from the original Stroop (1935) experiments; mean total response times (in seconds) for 100 items on a card

Experiment	Experimental condition	Control condition
Experiment 1: Reading words	43.30	41.00
Experiment 2: Naming colours	102.27	59.76

Note: In Experiment 1, the experimental condition involved reading words printed in incompatible colours and the control condition involved reading words printed in ordinary black font. In Experiment 2, the experimental condition involved naming colours of words with incompatible names and the control condition involved naming colours of colour patches.

await the advent of single-trial recording; it was actually introduced 30 years later by Dalrymple-Alford and Budayr (1966).

Stroop simply and elegantly explored an interference phenomenon. Overall, he saw differential practice as explaining the asymmetrical interference pattern across his two experiments, with reading words being much more practised than naming colours. He agreed with Peterson et al. (1925) that words evoked a single reading response whereas colours evoked multiple responses, an idea he saw as confirmed when he put it to further test three years later (Stroop, 1938). The reliability, size, and apparent simplicity of the effect named after him have continued to pique the interest of investigators for almost 80 years.

IMPACT AND CRITIQUE OF THE CLASSIC STUDY

It would be hard to overestimate the impact of Stroop's hallmark task, in that it is featured in virtually every introductory and cognitive textbook in the discipline and is that rarest of phenomena – one whose influence has increased rather than declined over time. As evidence of this influence, according to the *Web of Science*, the topic of the Stroop effect appears in 2,800 articles and has attracted over 70,000 citations. I have noticed that many articles involving the Stroop effect do not even cite his classic article, no doubt because 'everybody knows the Stroop effect', so these numbers, high as they are, likely represent a considerable underestimate. The number of articles on the topic of the Stroop effect increased from 42 in the 1980s, to 462 in the 1990s, to 1,350 in the 2000s. The corresponding citations for articles published in these three decades are 1,406, 25,813, and 38,765. That is a truly extraordinary impact.

Yet it did not start out that way. Indeed, for 30 years after the study was published, almost no research pursued the phenomenon or its explanation, with its visibility almost entirely confined to use as a component of psychometric tests (e.g., Thurstone, 1944). But just when Jensen and Rohwer (1966) reviewed this applied use of the Stroop task, it was beginning to attract attention in the realm of basic cognitive research on attention and learning.

Three factors were crucial in reviving interest in what we now know as 'Stroop interference' as a way to explore basic cognitive processes such as attention and learning. The first was a systematic study exploring the phenomenon and reintroducing it to a new generation. That study was published by Klein (1964). In his article, Klein showed that the degree of interference with colour naming caused by the to-be-ignored verbal item was a function of the nature of the verbal item: interference was greatest when the irrelevant words were incongruent members of the set of colours to be named, dropped by 50% as he moved to other colour words not in the response set, and then gradually declined further across high frequency words, low frequency words, and non-words. Klein's study was well timed to reignite interest because its publication coincided with the emergence of the second key factor – a new method. With the appearance of computer-controlled experiments came the possibility of presenting individual Stroop trials to obtain trial-by-trial response times, a procedure that Dalrymple-Alford and Budayr (1966) demonstrated to be viable and that has become by far the dominant paradigm since then. Indeed, the rapid growth in interest in the 1960s shortly led to the third key factor – the appearance of the first comprehensive review article on the Stroop effect as a basic cognitive phenomenon, published by Dyer (1973). Since that time, there has been no looking back: thousands of studies involving the Stroop effect have been published in the past 40+ years.

For a decade or so following the Klein (1964) study, the focus of much of the research on the Stroop effect was on where in the sequence of processing the interference arose. This fit with the then prevailing view of processing as a sequence of serially executed stages (cf. Sternberg, 1969). Interference was widely viewed as the consequence of relative speed of processing, essentially ratifying the ideas of Cattell (1886) and Stroop (1935) that the word dimension was processed faster than the colour dimension, resulting in a race in which, when the task was colour naming, the wrong dimension won. This was often referred to as a 'horse race' model. But where exactly did interference arise in the race? For some, the problem was near the start, during encoding, making it a problem of 'early selection'. In their perceptual-encoding account, Hock and Egeth (1970) argued that the encoding of ink-colour information was slowed by the incompatible information from a colour word (as opposed to a neutral control). But much evidence around the same time and certainly later conflicted with this account. The most influential explanation came to be the response selection account, viewing interference as a 'late selection' problem (e.g., Morton & Chambers, 1973; Posner & Snyder, 1975). Posner and Snyder (1975, p. 57) put this very clearly:

> First, the usual Stroop effect arises because of response competition between vocal responses to the printed word and the ink color. ... Second, the direction of interference depends upon the time relations involved. Words are read faster than colors can be named, thus a color naming response receives stronger interference from the word than the reverse. ... Third, words often facilitate the vocal output to colors with which they share a common name. ... These three results suggest that color naming and reading go on in parallel and without interference until close to the output.

By the mid-to-late 1970s, the idea that processing was quite strictly sequential had lost currency in cognitive psychology, and parallel processing ideas came to hold sway, as seen in the work of Townsend (1976), Taylor (1977), and others. The parallel view – that word and colour were processed simultaneously with cross-talk throughout processing, meshed much better with the Posner and Snyder (1975) automaticity account, and this has been the dominant perspective ever since, whether processing of the response-irrelevant word is seen as 'automatic' or simply as more fluent than processing of the response-relevant colour.

A couple of studies illustrate results that fit well with this parallel view and not with the sequential view. Consider first a study by Glaser and Glaser (1982). Using the individual item procedure and separating the word from the colour, they directly tested the sequential speed of processing idea. They varied the stimulus onset asynchrony, presenting the word prior to the colour or the colour prior to the word over a range of temporal gaps. Their critical finding came from the situation where the task was to read the word but the colour information came first. Surprisingly, there was no evidence of interference with word reading even when an incompatible colour appeared 400 milliseconds before the word. Under any version of the sequential speed of processing account, a reversed Stroop effect – that is, incompatible colours interfering with word reading – should have appeared with such a long lead time for the colour, so finding no interference at all in this situation contradicted this type of account.

Shortly thereafter, Dunbar and MacLeod (1984) took a different approach, manipulating the ease of reading words by spatially transforming them, for example, turning them upside down and backwards. Time to read colour words aloud increased radically when they were presented in unusual orientations. Yet even when reading a colour word became substantially slower than naming the colour in which the word was printed, robust Stroop interference – virtually undiminished – was still observed. Perhaps most striking, when word reading was extremely slow, a reversed Stroop effect co-occurred with the standard Stroop effect. Like the Glaser and Glaser (1982) findings, this pattern of data is thoroughly inconsistent with the sequential speed of processing account. Indeed, research using the Stroop task was instrumental in changing the prevailing view of the stream of processing from a sequential to a parallel framing.

The 1970s and 1980s saw immense growth in research on the Stroop task and its many variants, as reviewed by MacLeod (1991a). As just a few illustrations, the Stroop task was used to test theories not only of attention (e.g., Neill, 1978) and automaticity (e.g., Kahneman & Chajczyk, 1983; MacLeod & Dunbar, 1988), but also of semantic memory (e.g., Klein, 1964; Warren, 1972), bilingual memory organisation (e.g., Mägiste, 1984; Preston & Lambert, 1969), and reading (e.g., Martin, 1978), among others. For the centenary of the establishing of the American Psychological Association, Stroop's (1935/1992) article was selected as one of the classics worthy of republication, and was identified as the 'gold standard' of measures of attention, one of the few widely-known tasks where related research has continued to grow as opposed to declining with the passage of time (MacLeod, 1992).

In the past 20 years, interest in Stroop interference has not abated. Indeed, the task has become a favourite of cognitive neuroscientists interested in basic brain processes and in the disruption of normal brain processes caused by a variety of disorders. This was already true in 2000 (see MacLeod & MacDonald, 2000), but Stroop-related research on basic brain mechanisms of cognition has accelerated since then, with interference used as a measure of inhibition (e.g., Mitchell, 2005) or episodic memory retrieval (e.g., Egner & Hirsch, 2005) and, more often, cognitive control (e.g., Carter et al., 2000; Herd, Banich, & O'Reilly, 2006) processes in brain regions identified by fMRI and other imaging techniques. The clinical work is even more extensive, including research on such diverse diagnoses as schizophrenia (e.g., Minzenberg, Laird, Thelen, Carter, & Glahn, 2009) and ADHD (Bush et al., 1999), where investigators have sought to identify the brain regions affected by the disorder.

NEW EXPLANATIONS

Theoretical work has also developed in the past quarter-century, with notable new theories coming forth from different cognitive domains. The first and best known was the connectionist theory of Cohen, Dunbar, and McClelland (1990). As a starting point, they took the findings of MacLeod and Dunbar (1988) – that interdimensional interference was a direct function of training or practice on each dimension, implying that automaticity is continuous, not all or none. Then, in a parallel distributed processing framework, Cohen et al. argued that automaticity depends on the strength of a processing pathway, with strength increasing over extended training. When the model, a neural net, was trained more on reading words, it was able to produce many of the key findings in the Stroop literature. Automatic word reading did appear to be continuous, emerging gradually with practice. This model has stimulated a great deal of theoretical development since its introduction, both in the Stroop domain and beyond.

Roelofs (2003) disputed this association-based approach, instead building his model on the foundation of a psycholinguistic theory of word production and the idea of production system rules. Essentially, he argued that the Stroop effect is the result of processing interactions within the language-production system and of goal-referenced control processes. In his view, attentional selection in the Stroop task is in fact selection for responding verbally. This selection is based on the individual's goals for action, specifically for verbal action, with the model incorporating both automatic and expectancy-based elements of verbal responding. This model also was very successful in encompassing many of the findings that MacLeod (1991a) had identified as critical for any theory to capture.

In yet another approach, Melara and Algom (2003) built their model on fundamental perceptual principles, arguing that attentional selection results from two memory-based structures that accomplish selection by processing information within and across stimulus dimensions dynamically and without the need for consciousness. The result is that memories of presented and even unpresented dimensional values are retrieved from trial to trial, such that the recent past – and even the more distant past – both influence the present. One of these structures is *dimensional uncertainty*, reflecting the degree of correlation of the dimensional values and the degree to which co-occurrences of those values are unexpected based on memory. The other is *dimensional imbalance*, reflecting the degree of salience of the dimensional values: typically, experimenters specify colour naming as the task, but subjects are vastly more experienced with reading words. Each of these structures plays a role in governing the excitation accruing to the target dimension as well as the inhibition applied to the distractor dimension and to the memories of prior episodes.

The Melara and Algom (2003) model grew out of empirical work by Melara and Mounts (1993) demonstrating that Stroop interference is to a considerable extent the result of episodic history – experience with the various possible stimuli in the experiment. This was the source of the dimensional imbalance structure in the model. Basically, their claim is that the word-colour contingency matters a great deal, a fact that has been under-appreciated in the literature. A major implication is that individual stimuli seen more frequently will be responded to faster than those seen less frequently, other factors being equal. This may well explain why congruent trials are faster than incongruent trials in the Stroop task. Researchers ordinarily design their experiments to have an equal number of trials in each condition, but this necessarily means that there are more incongruent than congruent stimuli across trials (e.g., given four colours, there are four congruent colour–word combinations but 12 incongruent combinations). Consistent with this idea, when Melara and Mounts (see also Sabri, Melara, & Algom, 2001) equated stimuli rather than conditions, the response time advantage for congruent items sharply decreased. As for the dimensional salience structure, they argued that words typically are more discriminable than colours, making words more salient despite instructions to devote attention to colours. When they manipulated dimensional discriminability, they found that making the colours more discriminable or the words less discriminable again sharply reduced Stroop interference. In addition to being consistent with their theory, these results suggest that considerably more thought needs to be given to how Stroop experiments are constructed.

HOW THE CLASSIC STUDY ADVANCED THINKING

Stroop could not have known the continuing prevalence and impact that his task would have – interestingly, when Jensen (Jensen & Rohwer, 1966) spoke to him in the mid-1960s, Stroop was not very interested (see MacLeod, 1991b). At the time of his dissertation, Stroop's project was far removed from the ethos of the day, dominated as the times were by behaviourism. Quite obviously, the size of the behavioural effect – it is one that we can feel almost as soon as we begin performing the task – and the simplicity of the paradigm have been strong attractors for researchers. As well, interference of one type or another is among the few real tools that we have available to explore cognitive mechanisms, and Stroop interference is without doubt the best-known measure of interference.

As already noted, the Stroop task has been put to a wide variety of uses, particularly if its many variants are included. Among the most prevalent variants are the picture–word task (where the task is to name a simple picture, ignoring a word printed on top of the picture; see Dell'Acqua, Job, Peressotti, & Pascali, 2007; van Maanen, van Rijn, & Borst, 2009, on the debate concerning how closely these two tasks are related) and the counting Stroop task (where the task is to ignore a set of digits while counting how many of them there are; see, for example, Bush et al., 1999). But probably the most frequently used variant comes from the clinical literature: the emotional Stroop task (see Williams, Mathews, & MacLeod, 1996, for a review). Here, words related to one's psychopathology (e.g., spider-related words for someone with arachnophobia) are found to be slower to colour name than are control words. This version of the task has been heavily used to explore a host of clinical diagnoses, although whether it is really a true Stroop analogue is a subject of debate. I am inclined to agree with Algom, Chajut, and Lev (2004) who maintain, based on a conceptual analysis and a series of experiments, that the interference observed for the emotion words relative to the control words in the emotional Stroop task reflects a generic slowdown resulting from the threat embodied in the emotional words, not the selective attention influence underlying the classic colour–word Stroop effect. People respond very slowly in the emotional Stroop task, as if they are watching for the emotion-related words. Moreover, the response competition so integral to the classic Stroop effect is absent in the emotional Stroop task.

A reasonable question to ask at this juncture would be: 'What exactly does the Stroop task measure?' Despite its widespread and frequent use, the answer to that question is not straightforward. It is most widely seen as a measure of attentional selectivity, or more properly of its failure (e.g., Melara & Algom, 2003). But it is also frequently taken to be a measure of inhibition, even of neural inhibition (e.g., Brittain et al., 2012). My colleagues and I have argued against the inhibition perspective (e.g., MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003), and the work of Miyake, Friedman, and colleagues (e.g., Friedman & Miyake, 2004) has argued that the concept of inhibition may be over-extended. Some have argued that it is simply an index of extent of learning (e.g., MacLeod & Dunbar, 1988), as even Stroop (1935) himself maintained. And in the past 20 years or so, it has become widely used as an indicator of executive or cognitive control (e.g., Meier & Kane, 2013). Certainly, one goal for future research will be to try to ascertain what Stroop interference actually measures in cognitive processing, which in turn will help us to better understand cognitive processing more generally.

CONCLUSIONS

This very simple task has given us a great deal of insight into the operation of mind. Often, to capture thought in action, we need to see how it fails – what makes it slower or more error-prone. No situation provides a more obvious illustration of this failure than the Stroop task. Better learned information gets in the way of less well learned information, automatic responses trump more controlled ones, and we must keep at bay a more familiar response to be able to make a more novel response. The Stroop task is a reflection of all of these situations, and so continues to provide a valuable tool for exploring basic cognitive functioning as well as disruptions of that functioning.

FURTHER READING

(Complete citations are in the References section.)

MacLeod (1991a) presents the most comprehensive review of the voluminous Stroop literature to that point, although a great deal of research has been published in the over 20 years since then.

MacLeod (1991b) presents a brief biography of John Ridley Stroop, the man whose dissertation launched his eponymous task.

Cohen, Dunbar, and McClelland (1990) present the first detailed model of the Stroop task, also a landmark article in the world of connectionist modelling.

Melara and Algom (2003) offer an alternative, more perceptual account of the Stroop effect, pointing out some critical problems of method and interpretation.

Stroop (1935/1992) is the classic article, containing his dissertation research and written in a clear and engaging fashion, with straightforward analyses and good connections to the 'big picture' relevant to attention, learning, and memory.

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