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Stroop Paradigms and Stroop Effects: Origin, Variation and Controversy

Li Chen[1, *], Zhi Chen[2]

[1]School of Physical Education and Sports Science, Lingnan Normal University, Zhanjiang, China

[2]Zhanjiang Preschool Education College, Zhanjiang, China

Email address:
hunanchen323@163.com (Li Chen)

[*]Corresponding author

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Abstract: The Stroop paradigm is one of the classic experimental paradigms in cognitive neuroscience. This study starts with John Riddley Stroop's first color word test paper published in 1935, reviewing Stroop's own trade-offs between major and interest, and tracing the origins of the Stroop paradigm and Stroop effect. The author conducted a comprehensive collection and organization of Stroop related research published from 2003 to 2023, analyzing the current status of Stroop related research from three aspects: the quantity of literature, published journals and research institutions, and research hotspots. The results showed that the number of Stroop studies steadily increased year by year between 2003 and 2023, with Neurophysiology (in English) and Journal of Physiological Science (in Chinese) having the highest publication volume, The largest number of research topics is the Emotion-Stroop study. It has also been found that the diversification of Stroop variants and the computerization of Stroop tasks, combined with new technologies such as EEG, ERP, fMRI and eye trackers etc., have become new research trends. The timing of the Stroop effect and the "trend trap" of the Stroop task also were discussed and presenting realistic stimuli and improving response methods were suggested to enhance the ecological validity of the Stroop task.

Keywords: Stroop, Cognition, Unconscious, Validity

1. Introduction

Reaction time is a commonly used variable in experimental psychology, which can quantitatively reflect the characteristics of certain psychological activities. The Stroop task is an experimental method based on reaction time. Since the first appearance of the Stroop task in 1935 [1], after 88 years of sedimentation and expansion, the Stroop paradigm and various variants have become classic research paradigms in cognitive neuroscience and experimental psychology and have been widely used. Is there any change in the quantity of the Stroop task literature? What variants have been developed for Stroop paradigm? What aspects of research can be the Stroop paradigm applied to? What are the hot topics of Stroop research? Are there any controversies? In response to these issues, this article will start with John Riddley Stroop's doctoral thesis and discuss and analyze the research trends and current controversial issues of Stroop to provide reference for better application and development of the Stroop paradigm.

2. J. R. Stroop and Stroop Color-Word Task

In 1935, John Riddley Stroop, a Ph. D. in experimental psychology in the United States, published his doctoral paper "Studies of Interference in Serial Verbal Reactions" in the Journal of Experimental Psychology. In this paper, Stroop used five color words (red, blue, green, purple, and brown) and corresponding color blocks. A comparison was made between the reaction time of the named color blocks and the reaction time of the named color words (such as "red" words written in blue, green, purple, and brown ink, respectively). (Note: he did not directly compare the reaction time of colors, words "consistent", and "inconsistent"), and it was found that the reaction time of the latter one was much longer than that of the previous one. This difference in reaction time is

considered to be the interference effect of word meaning on color naming. This is the first appearance of the classic Stroop color-word task, and this paper is also a necessary reference for almost all subsequent Stroop studies. This color word test has also become a commonly used experimental paradigm for studying reaction conflicts. From Stroop's experience and research, it can be seen that:

2.1. Standing on the Shoulders of Giants

Although Stroop is commonly thought of when it comes to the "color-word task" nowadays, he is not the first person to study this phenomenon. Prior to him, some researchers, including James McKeen Cattell, have explored the issue of the time when people name object characteristics and object names, Experimental studies have also found that people spend much less time reading words (naming object names) than naming object characteristics (including colors) (see in [2]). Stroop himself mentioned 23 previous studies in the introduction of his paper. But on the basis of summarizing previous research methods and achievements, Stroop creatively utilized color words of different colors to concentrate the two tasks of "reading words" and "reading colors", causing conflicts. In this regard, he stood on the shoulders of giants. It can be said that scientific research is like "overlapping". Previous research is the "shoulder" of Stroop research, and Stroop's color-word task has also become the "shoulder" of future research.

2.2. The Trade-off Between Profession and Interest

From Stroop's life, it can be said that he was not very interested in the color-word task he created, or rather he was not interested in psychology. He only published three psychology papers throughout his life: one was his doctoral thesis, and the other was a review [3] of his research on the reasons for the differences in color and word reading time, as well as age differences, by researcher Ligon, Another article [4] is a comparative study on group judgment and individual judgment, but Stroop did not continue any research related to color words. From his experience, although he majored in experimental psychology, his true interest was in religion. He was a devout Christian who published seven religious works and regarded religion as his lifelong mission [5]. Obviously, Stroop chose his own interests when his major and interests were inconsistent, but the color-word task he pioneered provided inspiration and support for future related research.

3. Stroop Research Trends

3.1. Growth Literature Quantity

Although Stroop is not interested in the tests he created, many researchers have been inspired to conduct a large mount of related researches based on the Stroop color-word test, and the total amount of literatures on Stroop has been increasing year by year. As of September 16, 2023, the ScienceDirect database includes a total of 25,139 Stroop literatures in international journals; The total number of Stroop related literatures published in Chinese indexed by China National Knowledge Infrastructure (CNKI) is 341. Especially since 2010, the number of Stroop related literatures has exceeded 1000 per year (Figure 1).

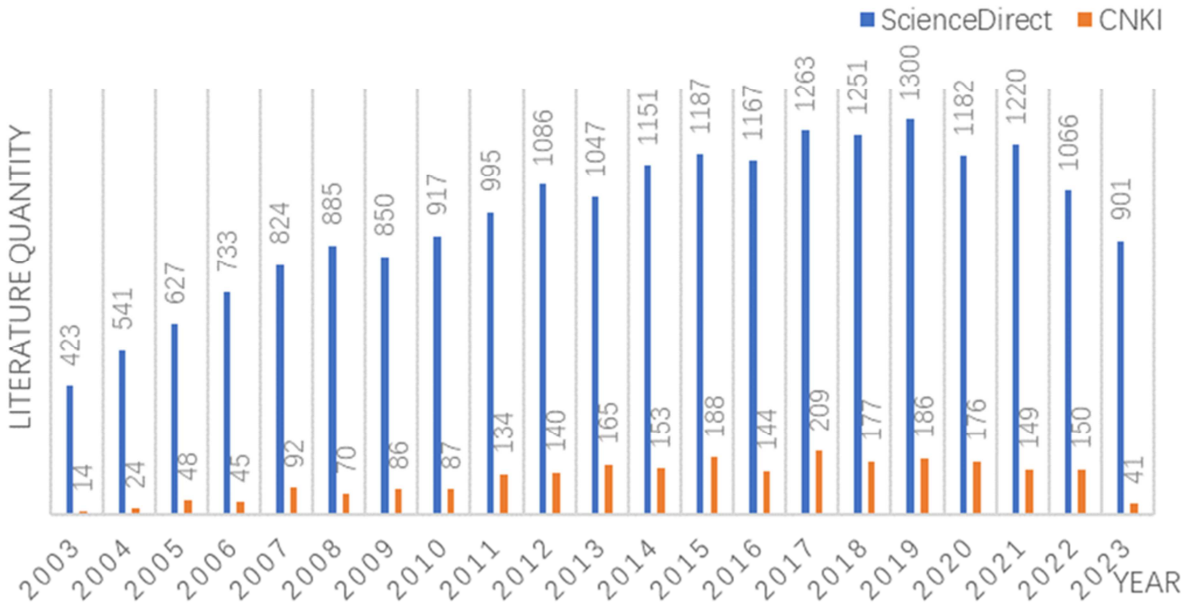

Figure 1. *Quantities of Stroop literatures retrieved by ScienceDirect and CNKI from 2003 to 2023 (as of September 16, 2023).*

3.2. Journals and Research Institutions

Stroop research is mainly published in psychology and clinical medicine journals such as Neuropsycologia and Schizophrenia Research (Table 1). The literature of Stroop in China is mainly published in psychological journals such as Psychological Science and Chinese Journal of Mental Health (Table 2).

Table 1. *Journals with the most Stroop literatures (top 10).*

No.	Journals	Literature Quantity
1	Neuropsychologia	827
2	Schizophrenia Research	811
3	NeuroImage	774
4	European Neuropsychopharmacology	581
5	Neuroscience & Biobehavioral Reviews	529
6	Biological psychiatry	481
7	Psychiatry Research	476
8	International Journal of Psychophysiology	432
9	Acta Psychologica	431
10	Cortex	427

Note: Data sourced from ScienceDirect (as of September 16, 2023)

Table 2. *Journals with the most Stroop literatures in China (top 5).*

No.	Journals	Literature Quantity
1	Journal of *Psychological Science*	66
2	Chinese Mental Health Journal	49
3	Acta Psychologica Sinica	41
4	Chinese Journal of Clinical Psychology	33
5	China Journal of Health Psychology	23

Note: Data sourced from CNKI (as of September 16, 2023)

The most master's and doctoral papers related to Stroop are from universities such as Southwest University and East China Normal University (Table 3). It can be seen that the Stroop task is mainly applied in the fields of psychology, medicine, and especially clinical medicine. As a research method based on reaction time in cognitive neuroscience, it is widely used to study the cognitive processing process of the brain.

Table 3. *Institutions with the most Stroop literatures in China (top 5).*

No.	Institutions	Literature Quantity
1	Southwest University	93
2	East China Normal University	44
3	Anhui Medical University	41
4	Soochow University	34
5	Northwest Normal University	32

Note: Data sourced from CNKI (as of September 16, 2023)

3.3. Research Theme

According to the objectives and contents, all these Stroop researches can be roughly divided into three categories: task variants, theoretical construction of effect mechanisms, and applied research.

3.3.1. Stroop Task Variants

The traditional color-word task is a sensitive and concise test method based on reaction time, which contains the possibility of change due to its simplicity. Based on the design of traditional color-word task, many researchers have cleverly modified, restricted or extended the stimulus materials, stimulus presentation methods, test scenarios, etc. to developed many Stroop variants.

Until now, the hotspots in Stroop research are the Emotion Stroop effect paradigm [6] and the Reverse Stroop paradigm [7]. Other variants including the Graph-Word Interference Stroop paradigm which commonly used in psycholinguistic research [8], the Digital Stroop paradigm [9], the Day-Night Stroop paradigm [10], and the Bilingual Stroop paradigm [11] have also been gradually developed. Figure 2 shows the changes in the number of studies on the Stroop paradigm variants from 2003 to 2023. The Emotion Stroop paradigm was the most used with 6817 studies in total, followed by Reverse Stroop paradigm (6055 literatures). Next in order are the Digital Strop paradigm (2038 literatures), Picture-Word Stroop paradigm (1823 literatures), Day-Night Strop paradigm (1266 literatures), and Bilingual Strop paradigm (700 literatures). The following focuses on the Emotion Stroop paradigm and Reverse Stroop paradigm.

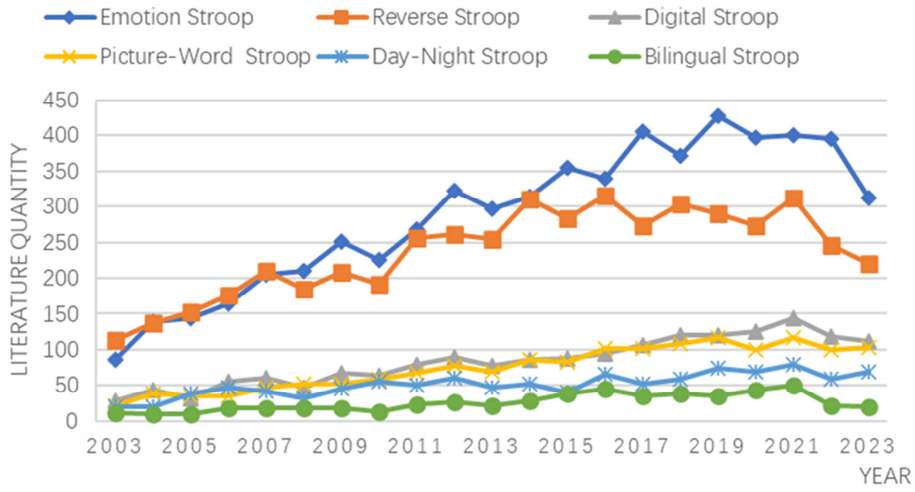

Figure 2. *Growth quantities of literatures about Stroop paradigms from 2003 to 2023 (ScienceDirect, as of September 16, 2023).*

(i). Emotion Stroop Paradigm

As mentioned earlier, in 1984, Gotlib and McCann replaced color words (red, blue, green, etc.) with emotion related words (such as war, cancer, kill, etc.) on the basis of the traditional Stroop color-word task. They studied the cognitive processing bias of individuals with emotional disorders and discovered the emotional effect, that is, the impact of emotional

information in stimuli on non emotional information. This study has become a precedent for Emotion Stroop research. At present, Emotion Stroop has gradually become most hot paradigm in Stroop research. The stimuli used in tests are no longer limited to emotional words, emoticons and some specific types of images (such as certain animal images) can be used as emotional stimuli to induce and produce specific emotional responses [12, 13].

(ii). Reverse Stroop Paradigm

The Reverse Stroop Paradigm was proposed by Logan (1984) and later improved by Merikle, Joordans and Stolz [14]. In their test, the initiating stimulus was a gray "RED" or "GREEN"; The target stimuli were red and green blocks. The probability of consistency between color words and color blocks in the experiment (usually 25%) is significantly lower than the probability of inconsistency between color words and color blocks (usually 75%). At this point, changing the SOA (stimulus on set asynchrony) between stimulus and masking revealed that in an unconscious state (SOA of 33ms), participants named color blocks faster in consistent scenarios than in inconsistent ones, exhibiting a typical Stroop effect. In the state of consciousness (SOA is 167ms), participants name color blocks in inconsistent situations faster than in consistent situations, resulting in a typical reversal of the Stroop effect. This paradigm is therefore called the Revers Stroop paradigm. The explanation for this is that in a conscious state, participants adopt a certain reaction strategy based on probability information, that is, they need to prepare for opposite color expectations when seeing color words. This paradigm is often used to study conscious and unconscious perception [15, 16].

3.3.2. Stroop Effect

With the improvement and deepening of Stroop research, researchers have discovered different effects such as interference, facilitation, dilution, and reversal in Stroop task.

(i). Stroop Interference & Stroop Facilitation Effect

The interference effect was first discovered by Stroop himself in color-word task, which is a phenomenon where the reaction time to inconsistent stimuli (such as the 'red' character written in blue) is longer than the reaction time to neutral stimuli (such as blue color blocks). Later, this phenomenon of higher response time and error rate to inconsistent stimuli than to neutral stimuli was called Stroop interference, while the phenomenon of lower response time and error rate to consistent stimuli was called Stroop facilitation. Commonly, the Stroop effect includes these two effects, referring to the phenomenon where response time and error rate to inconsistent stimuli are higher than those to consistent stimuli. It reflects the influence of word meaning information on color processing.

(ii). Stroop Dilution Effect

In 1983, Kahneman and Chajzyk [17] added color independent words as target stimuli to the Stroop color word task, and found that the Stroop effect was significantly reduced. They referred to this phenomenon as the 'Stroop dilution effect'.

(iii). Stroop Reverse Effect

The Stroop reverse effect refers to the effect that is opposite to the typical Stroop effect, as described in the previous 'Reverse Stroop paradigm'.

3.3.3. Stroop Effect Mechanism Theory

Why do Stroop tasks exhibit these effects? What are the mechanisms by which these effects occur? There are currently six widely recognized theories and models of effect mechanisms for addressing these issues, including the Relative Processing Speed theory, Automation Theory, Perceptual Encoding Theory, Parallel Processing Model, and Parallel Distributed Processing Model. These five earlier theoretical models were summarized by Macleod [2] during a review of relevant research on Stroop tasks over the past half century. The sixth model is the Construction Theory of the Stroop effect proposed by Robert and Daniel in 2003 [18]. The new theory has greater explanatory power and applicability, but it cannot completely replace existing theories. Various theories have explained the Stroop effect from different perspectives [19].

3.3.4. Application Research

The Stroop task, as a classic research paradigm for cognitive processing in the brain, has penetrated into many fields, especially in clinical medicine, psychology, including sport psychology. In the field of clinical medicine, Stroop tasks are often used for the diagnosis and treatment of chronic pain, dementia, epilepsy, cerebrovascular diseases, and other diseases [20-22]. It has also been applied to research on psychological issues such as personality disorders, emotional disorders, substance addiction, eating disorders, and schizophrenia [23-25]. Recently, there have been more and more research reports on the application of Stroop tasks in the field of sports and exercise, such as the application of Stroop tasks in the study of athletes' pre competition emotions, mental fatigue, cognition and other issues [26-28].

4. Stroop Research Features

4.1. Diversified Development of Stroop Paradigm

From the nearly 90 years of development of Stroop tasks, it can be seen that Stroop tasks contain rich variability. With the continuous deepening of research, the Stroop paradigm family is constantly growing. Starting from the traditional color-word Stroop task, more and more new variants have been developed (in addition to Emotion Stroop paradigm and Reverse Stroop paradigm, as well as the recently proposed Counting Stroop paradigm, Spatial Stroop paradigm, and Auditory Channel Stroop paradigm based on digital Stroop etc.), and more and more effects have been discovered (reverse effect, dilution effect, etc.), More and more explanatory theories of mechanisms have been proposed, such as the Comprehensive Model Parallel Distributed Processing Model proposed on the

basis of early Relative Processing Speed Theory and Automated Processing Theory, as well as recent Construction Theory. The Stroop paradigm is like a rich mine, with new treasures constantly being excavated as they become deeper and wider. The development and application of these new tests based on reaction time not only enriches the Stroop theory, but more importantly, it gradually unveils the veil of cognitive function in the brain.

4.2. Combined Application with New Technologies

With the development of computer technology, more and more accurate stimulus presentation and response recording techniques have been integrated into the Stroop task paradigm. Computerization of tests has become an important feature and trend in the development of Stroop research today. In 1935, Stroop used cards to manually present stimuli and stop watches for timing in his color-word task, which could only be accurate to 1/15 of a second. Gradually, slides replaced cards, and then computers replaced slides. Currently, the widely used hardware with precise timing and automatic testing software such as E-Prime and DMDX for stimulus presentation and reaction recording can be timed in millisecond. The sensitivity of the Stroop test has been greatly improved.

Meanwhile, as a classic paradigm for detecting cognitive processing in the brain, Stroop tasks are increasingly combined with EEG [29], ERP (Event Related Potential) [30], eye movement tracker [31] and fMRI (Functional Magnetic Resonance Imaging) [24, 32] and has more effectively revealed richer cognitive activities in Stroop task. These new methods and technological applications are advancing research on cognitive activities, further revealing the neural mechanisms of the brain.

5. Controversy

The Stroop task is a cognitive processing test method based on reaction time, so the balance between speed and accuracy is the core issue that need to be considered. In addition, based on existing Stroop research, there are currently two main controversies:

5.1. When the Stroop Effect Occur

With the increasingly sophisticated design of Stroop tests, especially the more precise timing in tests, different stimulus presentation times can lead to different Stroop effects, which has become an indisputable fact [14, 33]. However, it is a controversial and unanswered question about the exact time period during which Stroop effects occur [19]. Why is the time so important? One key reason is that it is related to how to obtain a pure unconscious perception, that is, where is the boundary point between subliminal and subliminal perception, or conscious perception and unconscious perception? Until now, the answer is still in the mist. Greenwald, Drain, and Abrams [34] proposed that subthreshold priming can only be achieved when the SOA between the initiating stimulus and the target stimulus is less than 100ms, but many studies have found that this data is too absolute. For example, Daza and Ortells [35] found that the subthreshold Stroop effect can occur not only at SOA 300ms, but also at SOA 400ms. These studies suggest that there may not be clear distinctions between supra and subthreshold levels, and perhaps there is no clear boundary between them even. Moreover, existing studies have suggested that when and what effects occur is not simply a matter of time, but rather the result of the interaction of multiple factors. For example, stimulus characteristics and attention levels can mutually compensate for the impact on stimulus perception [36, 37].

5.2. Ecological Validity: Trend Traps

Since the Stroop paradigm is conducted in the laboratory, ecological validity is undoubtedly an unavoidable issue. Among all the variants, the Emotion Stroop paradigm is the hot one, and its ecological validity has also attracted the most attention. The biggest challenge regarding the Emotional Stroop paradigm is that in the laboratory, people's response to emotional words is slower than that to neutral words [38], while outside the laboratory, it is well known that people's response to emotional stimuli, especially dangerous stimuli, is faster than that to neutral stimuli. Why does this completely opposite result occur? What are the factors between inside and outside the laboratory that contribute to this difference? A possible explanation for this is that the situation created by emotional words or images in the laboratory has a relatively small effect on inducing emotions, or that the intensity of the emotions induced is relatively low, meaning that the laboratory situation is not "realistic" enough, and therefore people's emotional experience is not "strong" enough, resulting in a less "rapid" response time, which is slower than outside the laboratory. Therefore, it can imagine that if the experimental design uses more vivid emotional stimuli (such as using material objects instead of pictures) and sets up Stroop tasks that induce higher emotional experience intensity (such as mild electric shock stimulation), it may be possible to observe more similar reaction time results in real life. Another possible explanation is that there is a difference between the reaction mode in the laboratory and that in real life. Most of the requirements for emotional stimulation in the laboratory are for the "button response" of extending both hands' fingers, which is far from the natural response in real life when facing emotional situations, especially threat situations. Because in real life, when facing threat situations, one often does not "extend their hands", but quickly "retracts their hands". Therefore, the "button response" required in the laboratory becomes an unnatural reaction, which affects the reaction speed. As Chajut, Mama, Levy and Algom [39] argued, the laboratory imposes a certain requirement for anti natural reactions without providing a choice to avoid threat scenarios, i e., setting up an "approach trap". So the existing theory of the emotional Stroop effect is challenged because it does not distinguish between approach avoidance responses. Therefore, it's believed that if we improve the response style in the experimental design and provide more life-oriented response options, then the Stroop task will undoubtedly have better

ecological validity and higher practical value.

6. Conclusion

Exploration is endless. Scientific research is a process of continuous exploration in the face of challenges. After 88 years of exploration and development, the Stroop paradigm has become a classic paradigm among numerous methods and has been widely applied. However, we all know that although methods are the 'most useful knowledge', they always serve the content. Therefore, when conducting relevant research, we should deliberately select appropriate methods based on the specific research purposes and content.

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