

*Reduced Stroop interference for opponent colors may be due to input factors: Evidence from individual differences and a neural network simulation.*

Bruno Laeng, Torstein Låg, and Tim Brennan

Department of Psychology

University of Tromsø

Address correspondence to Bruno Laeng, Ph.D., Department of Psychology, University of Tromsø, Åsgårdveien 9, N-9037 Tromsø, Norway; e-mail: [bruno@psyk.uit.no](mailto:bruno@psyk.uit.no)

This is a post-print (final draft post-refereeing) of Reduced Stroop interference for opponent colors may be due to input factors: Evidence from individual differences and a neural network simulation, *Journal of Experimental Psychology: Human Perception and Performance*, 31, 438-452. © 2006 American Psychological Association

This article may not exactly replicate the final version published in the APA journal. It is not the copy of record.

## *Abstract*

We examined how sensory or input factors can influence the strength of interference in the classic Stroop color-word task in 1) human subjects differing in color discrimination ability and 2) in neural network simulations (with different input layer implementations). Specifically, we first established that in a single-trial computerized version of the Stroop task when color-word pairs were incongruent, opponent color pairs (e.g., BLUE in yellow) showed reduced Stroop interference compared to non-opponent color pairs (e.g., BLUE in red). In addition, during the same session, participants had their color discrimination ability measured by standard color vision tests (i.e., Farnsworth-Munsell 100 Hues, and Ishihara Plates). It was found that error rates in the Farnsworth-Munsell 100 Hues test correlated positively with the amount of Stroop interference. The neural network simulations (i.e., variants of Cohen, Dunbar and McClelland's, 1990, model) showed that a trichromatic input layer alone was able to simulate these findings.

*Reduced Stroop interference for opponent colors may be due to input factors: Evidence from individual differences and a neural network simulation.*

The “Stroop effect”, in either its classic form (i.e., naming the color of colored words; Stroop, 1935) or its less colorful variations (e.g., naming drawings overlapping words), has been central in cognitive psychology as well as of great interest for clinical psychologists, psychiatrists, and neuroscientists (cf. MacLeod, 1991; Brown et al., 2002). The continuing and renewed interest in what outside of academia is considered a rather amusing and bizarre verbal teaser, may be due to the belief that “Stroop” effects are helpful in understanding attention, perception, and reading, as well as the cognitive and neural mechanisms behind inhibitory effects, psychological mechanisms like interference, controlled versus automatic processing, etc.

At its inception, the investigation of the interference of words’ meanings on object properties’ naming was mainly motivated by an interest for investigating individual psychological differences (cf. Jensen & Rohwer, 1966). Indeed, individual differences in the degree of Stroop interference are known to be amongst the most reliable or stable measures. Moreover, despite individual variation in the size of the effect, the relative differences of scores of congruently and incongruently colored words (as well as those of control conditions) maintain an impressive regularity at the group level and the same rank order of magnitude can be observed for nearly all subjects (e.g., Jensen and Rohwer, 1966, failed to find a single exception in a study of over 400 subjects).

As pointed out in MacLeod’s (1991) review, despite a great many articles that have examined the relation between Stroop interference and some individual difference parameter, the purpose of most of these studies has clearly not been to explain the Stroop effect. There

are however notable exceptions and in recent years several studies have focused on how the Stroop effect varies as a function of various individuals' aspects. For examples, Kane and Engle (2003) have shown that individual differences in working memory can predict Stroop performance, and Yee and Hunt's (1991) have examined individual differences on Stroop "dilution" (i.e., the interference of a color word on the naming of a color pattern is reduced if another, neutral, word is displayed simultaneously; Kahneman & Chajczyk, 1983). Thus, it appears that the study of individual differences can help to unravel some of the mechanisms underlying the effect. In the present study, we focused specifically on the following hypothesis: if some of the interference in color-word Stroop originates at the perceptual level (Seymour, 1977; Klopfer, 1996), then differences in color perception skills among individuals should have an impact on the degree of Stroop interference.

A simple way to study the role of perceptual processes on the Stroop effect could be to investigate individual differences at the input, or sensory, level of color processing. Individual differences in sensory discriminations may also be conceptualized as changing the "landscape" of color space. Assuming that the color and the word (naming a different color) activate different regions in color space, these regions might differ between individuals, both in extent and overlap. For example, in a Stroop trial where the color is 'green' and the word 'BLUE', the two activated regions of color space would be further apart in an individual with good blue-green discrimination ability than in another individual with less good blue-green discrimination. Consequently, the word blue would interfere to a lesser degree in individuals who are able to discriminate well blue from green than in individuals who make poor discriminations between these two colors.

Some studies have already examined the effect of input factors. Some have looked at the relations between various modes of stimulus input and response output (e.g., Virzi & Egeth, 1985; Lu & Proctor, 2001). Hock and Egeth (1970) might have been the first to

propose a perceptual-encoding account where one of the sources of interference is hypothesized to occur at an “early” selection stage, i.e. the perceptual encoding stage of the ink-color information. In other words, color words distract (and cause slowing) from encoding ink color. More recent models (e.g., Kornblum et al., 1999; Zhang & Kornblum, 1998; Zhang, Zhang & Kornblum, 1999; Melara & Algom, 2003) of the Stroop effect have clearly stressed the role of perceptual processes in the Stroop color-naming effect. We would also note that if input factors have an organizational effect on conceptual and semantic space, then perceptual encoding should be considered particularly relevant for a complete understanding of the Stroop effect.

However, according to MacLeod (1991), there seems to be a widespread belief that it is the processing subsequent to encoding that is most important in the Stroop effect. Perhaps due to such a belief, most computational models of the Stroop effect have not given specific relevance to input factors. The available and most advanced network simulations (e.g., Cohen, Dunbar & McClelland, 1990; Phaf et al., 1990; Zhang, Zhang & Kornblum, 1999; Kello, Plaut & MacWhinney, 2000; Roelofs, 2003) have not explored specific effects due to changes at the input layer. In particular, no attempt has been made to simulate basic properties of human color receptors and early color processing stages, like trichromacy (i.e., the organization of input by “L”, “M”, and “S” cone types) or color opponency (i.e., “L-M” and “S-(L+M)” mechanisms). Therefore, the influence of such variables on the behavior of such networks, and their ability to reproduce human data, is still not known. Yet, we surmise, some of the known effects of associative strength or semantic distance of color words from the to-be-named colors (e.g., Klein, 1964; Sichel & Chandler, 1969; Klopfer, 1996) may be accounted for, at least in part, by a specific organization of a network already specified by the structure of the input layer.

The evidence we present below indicates that individual differences in color encoding do play a role in determining the strength of the Stroop effect. In addition, we explore the role of input factors in variants of the classic Stroop neural network model of Cohen, Dunbar, and McClelland (1990).

*Experiment 1: Human Stroop performance.*

Experiment 1 A. In the experimental study with human participants, we used a single-trial computerized version of the classic color-word Stroop task (cf. Salo et al., 2001), with color and word pairs forming either congruent or incongruent matches. Two groups of subjects responded by pressing keys labeled with appropriate color patches (each group with different orderings of the labels) and a third group by verbal responses. All combinations of color-name pairs between the two basic pairs of opponent colors (i.e., blue, yellow, red, and green) were used.

First of all, we expected to find that color-word pairs with opponent colors (i.e., with the largest distance in color space) would reduce the strength of Stroop interference (i.e., the difference in RTs between incongruent and congruent trials) compared to non-opponent color-name pairs (i.e., with an intermediate distance in color space). This finding would replicate the similarity effects observed in previous studies (e.g., Klein, 1964; Klopfer, 1996). In addition, we expected to find that participants' differences in their color discrimination abilities, as measured by the Farnsworth-Munsell 100-hue Test and the Ishihara Plates, would influence the strength of interference in the classic Stroop color-word task. Specifically, error rates in the color tests should correlate positively with the strength of the Stroop interference.

## Method

Participants. 182 students (mean age = 23; SD= 6) at the University of Tromsø (104 females and 78 males) volunteered to participate in a color-word Stroop experiment. Among these participants, 138 (72 females and 66 males) also received the color vision tests.

Stimuli. The words BLÅ, GRØNN, RØD, and GUL (Geneva font, size 48) were presented at the center of the computer screen over a white background. Henceforth these will be referred to as BLUE, GREEN, RED and YELLOW. Each word could be colored in 'blue' (RGB coordinates= 0; 0; 255), 'green' (RGB coordinates= 0; 255; 0), 'red' (RGB coordinates= 255; 0; 0), or 'yellow' (RGB coordinates= 255; 255; 0).

*Apparatus and Procedure.* The G, H, J, and K keys were relabeled with focal blue, green, red and yellow color patches. For one group of subjects (N= 111) the color patches were in the following sequence: red, blue, green, and yellow (the RBGY set). For another group of subjects (N= 42) the color patches were in the following sequence (from left to right): green, red, yellow, and blue (the GRYB set). This second group of participants was included as a control condition in order to establish that the hypothesized differences in interference between color-word pairs were not due to the specific ordering of the color-labeled response keys. Participants were requested to press with the index finger of their preferred hand, as quickly and as accurately as possible, the key with the color patch corresponding to the color of the word. A key press terminated the stimulus presentation while the PC recorded the correctness of the key press and the response time (RT) from the onset of the word to the key response. All participants used fingers of their preferred hand for the manual responses. The third group of subjects (N= 29) responded by naming aloud the word's color, which activated a microphone switch that terminated the stimulus presentation and the response time measurement.

The testing of color vision consisted of 1) the Farnsworth-Munsell 100 Hue Test (FM 100-hue) and 2) the Ishihara Plates. The Farnsworth-Munsell 100 Hue Test (GretagMacbeth ©) is a simple and effective method for testing color discrimination. It consists of four sets of plastic caps in which the colors are mounted. There are a total of 85 moveable caps of same brightness representing hues along the complete human “circular” color space (equally in all strengths from neutral to high purity). The task is to rearrange the caps, from an initial random arrangement, according to color similarity between two fixed reference caps. The error score for a cap is calculated as the sum of the differences between the caps adjacent to it. Mantere and colleagues (1995) have calculated the correlation matrix of the cone responses of the 85 FM 100-hue caps and determined eigenvectors of the matrix; this showed that the first three eigenvectors can be interpreted as the opponent color signals and the non-opponent color signal. Thus, the normal observer can determine the color of a cap by using two opponent color signals; for color blind persons (dichromats) one or the other opponent signal is defective, and errors occur during the test. The test was administered by placing the caps on a table under a halogen lamp (about 6500° Kelvin illumination). Scoring of errors was performed according to the standardized FM 100-hue scoring system, using the GretagMacbeth © software.

The Ishihara test consists of 14 pseudo-isochromatic plates made of colored circles of various sizes, representing double-digit numbers inscribed inside a circle. The Plates are published by the American Optical Corporation (Beck Engraving Company ©) and they are typically used clinically for testing color perception. In the task, participants must simply name each of the numbers (allowing 2 seconds for a response). Omissions and incorrect responses are recorded on a score sheet by the experimenter. Incorrect response to 4 or less plates indicates normal vision, whereas incorrect response to 5 or more plates indicates



defective red-green vision; however, high error scores in the test do not classify the type of red-green defect or the amount of defect.

There were a total of 96 trials in the Stroop task; 48 trials showed congruent color-word pairs (e.g., BLUE in blue), 24 trials showed incongruent “opponent” color-word pairs (e.g., BLUE in yellow), and 24 trials showed incongruent “non-opponent” color-word pairs (e.g., BLUE in red). The trials presentation order was completely randomized by use of Superlab © software. Half of the 138 participants who completed all tests received the color vision test before the Stroop task, whereas the other half performed the tasks in the reverse order. Sex as a factor was taken into account in the following analyses. Although the presence of sex differences in Stroop interference remains controversial (cf., MacLeod, 1991, p. 184), it is well known that female participants have overall better color vision than the males (cf. Pickford, 1951).

### *Results*

The Opponent Colors Reduced Stroop Effect. We first calculated descriptive statistics for each participant, obtaining mean response times (RTs) for correct responses and error rate for each combination of the variables Word Color (i.e., blue, green, red, and yellow), Word Name (i.e., BLUE, GREEN, RED, and YELLOW).

Error rates were generally extremely low. Mean % error rates were calculated for each participant based on those trials where the Word Name spelled out the Word Color (e.g., BLUE in blue); this factor was renamed the Congruent color condition. Similarly, mean % error rates were calculated for trials that paired opponent colors (i.e., BLUE in yellow, GREEN in red, RED in green, and YELLOW in blue); this factor was renamed the Opponent color condition. Finally, mean % error rates were calculated for trials that paired non-opponent colors (i.e., BLUE in green, BLUE in red, GREEN in blue, GREEN in yellow, RED

in blue, RED in yellow, and YELLOW in green, YELLOW in red); this factor was renamed the Non-opponent color condition. A repeated-measures analysis of variance with Condition (Congruent, Opponent, Non-opponent) as the within-subject variable and mean % errors as the dependent variable showed no significant effect of Condition,  $F(2,352) = 0.8$ ,  $p < 0.41$  (Congruent: mean % error = 2.4, SD= 3.2; Opponent: mean % error = 3.1, SD= 3.4; Non-opponent: mean % error = 3.6, SD= 3.6).

The same averaging procedure described above was applied to RTs to obtain, for each participant, mean RTs in the Congruent, Opponent, and Non-opponent color conditions. RTs from trials on which errors occurred were excluded from analyses of the RTs, and trials with RTs greater than 3 standard deviations (SDs) from each individual's mean RT for that cell were treated as outliers and excluded from all subsequent analyses (less than 1% of the total data were excluded by this trimming rule).

The first analysis performed on RTs as the dependent variable was a repeated-measures analysis of variance with Condition (Congruent, Opponent, Non-opponent) as the within-subject variable, Sex (female, male) and Response Type (Keys G-R-Y-B; Keys R-B-G-Y; microphone). The analysis revealed a main effect of Condition,  $F(2,352) = 80.9$ ,  $p < 0.0001$ . As expected (see Figure1), participants evaluated Congruent color-word pairs (mean RT= 758 ms; SD= 141) faster than Opponent pairs (RT= 810 ms; SD= 147), whereas Non-Opponent pairs were evaluated the slowest (mean RT= 848 ms; SD= 168). Fisher's PLSD post-hoc tests confirmed that the differences were significant for each combination of conditions, Critical Difference= 31.4 ms;  $-38 < \text{Mean Differences} < -90$ ;  $0.02 < p < 0.0001$ .

-----  
*Figure 1 about here*  
-----

There was also a main effect of Sex,  $F(1,544) = 14.2, p < 0.0002$ . Female participants evaluated color-word pairs faster (mean RT= 788 ms; SD= 160) than the male participants (mean RT= 834 ms; SD= 148). In order to assess whether the sex difference appeared not only in the absolute speed to different conditions but also in the strength of the Stroop effect (i.e., the difference in RTs between the averaged incongruent conditions and the congruent condition), we performed an additional ANOVA with Sex (female, male) as the between-subjects factors and Stroop strength as the dependent variable. This confirmed a larger Stroop effect in males (mean RT= 82.1; SD= 61) than in females (mean RT= 61.9; SD= 51),  $F(1,180) = 5.9, p < 0.02$ .

In addition, there was a main effect of Response Type,  $F(2,176) = 6.3, p < 0.002$ . Participants evaluated color-word pairs the slowest with verbal responses (mean RT= 852 ms; SD= 201) and the fastest when matching key presses to color patches with opponent colors adjacent to one another, i.e. the Keys G-R-Y-B condition (mean RT= 762 ms; SD= 142). The other condition (Keys R-B-G-Y) showed an intermediate speed (mean RT= 809 ms; SD= 145). Fisher's PLSD post-hoc tests confirmed the differences between each combination of conditions, Critical Difference = 31 ms,  $-38 \text{ ms} < \text{Mean Differences} < -90 \text{ ms}; 0.02 < p < 0.0001$ . There was also a significant interactive effect between Response Type and Condition,  $F(4,352) = 4.4, p < 0.002$ . As shown in Figure 1, the differences in RTs between conditions were greater when participants responded by the use of a microphone than by use of key presses. To further explore these effects, we performed a separate ANOVA with Response Type as the fixed factor and Stroop Strength as the dependent variable. This ANOVA showed that microphone responses led to the strongest Stroop interference (mean RT difference= 103 ms), intermediate with arbitrary mapping of keys to colors (i.e., Keys R-B-G-Y: mean RT difference= 71 ms), and weakest Stroop with the more consistent mapping of keys to colors, where adjacent keys map onto opponent colors (i.e., Keys G-R-Y-B: mean RT difference= 48

ms),  $F(2,179) = 8.6$ ,  $p < 0.0003$ . Fisher PLSD post-hoc tests confirmed that all conditions differed significantly from one another,  $19 \text{ ms} < \text{Critical Difference} < 26 \text{ ms}$ ,  $-23 \text{ ms} < \text{Mean Differences} < -54 \text{ ms}$ ;  $0.02 < p < 0.0001$ .

In order to evaluate if the individual color-word pairs had different impact on the degree of Stroop interference, we performed an additional repeated-measures ANOVA with each Word-Color pair (i.e., the 4 congruent pairs, the 4 opponent pairs and the 8 non-opponent pairs) as separate levels of one within subject factor and mean RTs as the dependent variable. This ANOVA showed that the Word-Color pair was significant,  $F(15,2055) = 6.2$ ,  $p < 0.0001$ . Fisher PLSD post-hoc tests confirmed that all 4 congruent Word-Color pair differed significantly from all of the opponent and non-opponent pairs (Critical Difference = 41 ms,  $41 \text{ ms} < \text{Mean Differences} < 118 \text{ ms}$ ;  $0.0001 < p < 0.05$ ). In addition, the post-hoc tests failed to reveal any significant difference among the congruent Word-Color pairs ( $4 \text{ ms} < \text{Mean Differences} < 32 \text{ ms}$ ). The post-hoc tests also confirmed that several of the opponent Word-Color pairs differed significantly from non-opponent Word-Color pairs (i.e., BLUE-yellow and GREEN-red vs. RED-blue and RED-yellow; YELLOW-blue vs. BLUE-red, GREEN-yellow, RED-blue, and RED-yellow; RED-green vs. RED-blue and RED-yellow; Critical Difference = 41 ms,  $41 \text{ ms} < \text{Mean Differences} < 60 \text{ ms}$ ;  $0.04 < p < 0.05$ ). Finally, the post-hoc tests failed to reveal significant differences among the opponent Word-Color pairs ( $1 \text{ ms} < \text{Mean Differences} < 8 \text{ ms}$ ) or among the non-opponent Word-Color pairs ( $1 \text{ ms} < \text{Mean Differences} < 37 \text{ ms}$ ). Figure 2 illustrates the mean RTs for each individual Word-Color pairs.

-----

*Figure 2 about here*

-----

Individual Differences in Color Vision. In the Farnsworth-Munsell 100 Hue Test (FMH), mean error rate was 57.8 (SD= 29.4). Performance on the test ranged widely (from 12 to 156). Four participants, all males, scored more than 2.5 SDs higher than the whole group's mean. An ANOVA with Sex as the fixed factor and FMH scores as the random variable revealed that female participants had lower error rates (mean error score= 49; SD= 22) than the males (mean error score= 69; SD= 34),  $F(1,138)= 18.9, p < 0.0001$ . For the Ishihara Plates, the mean error rate was 1.03 (SD= 1.2) and scores ranged from 0 to 7. Four participants, 3 males and 1 female, scored over 4. An ANOVA with Sex as the fixed factor and scores on the Ishihara test as the random variable almost reached significance,  $F(1,138)= 2.9, p < 0.08$ . Again, female participants had lower error rates (mean error score= 0.9; SD= 1.0) than the males (mean error score= 1.2; SD= 1.4). Since the aim of the study was to evaluate individual differences, all subjects (including outliers) were included in the following analyses.

A simple regression between error scores in the Ishihara Plates as the regressor and error scores in the FMH as the dependent variable, revealed a significant positive relation and a correlation of moderate strength between the two color vision tests,  $Y = 47.6 + 9.6 * X, p < .0001; R = .39$ .

Individual Differences in Color Vision and the Stroop Effect. First we performed a simple regression between error scores in the FMH test as the regressor and Stroop strength (i.e., the difference between the averaged incongruent conditions and the congruent condition) as the dependent variable. This revealed a significant relation (see Figure 2) and a correlation of moderate strength between color vision abilities and the Stroop effect,  $Y = 31 + 0.8 * X, p < .0001; R = .41$ .

-----  
*Figure 2 about here*

-----

In order to evaluate whether the speed of color naming was influenced by individual differences in color perception, we also performed two separate simple regressions with error scores in the FMH test as the regressor and mean RTs for either opponent or non-opponent color-word pairs as the dependent variable. The regression on opponent trials revealed a significant relation and a correlation of moderate strength,  $Y = 718 + 1.9 * X$ ,  $p < .0001$ ;  $R = .38$ . The regression on non-opponent trials revealed a significant relation and a correlation of moderate strength,  $Y = 720 + 2.5 * X$ ,  $p < .0001$ ;  $R = .42$ . When the same regression analyses were performed between error scores in the Ishihara Plates and Stroop strength or RTs to either opponent or non-opponent trials, these failed to reveal any significant relationship,  $.05 < R < .08$ .

Finally, our account would also predict that individuals showing specific difficulties in color discriminations within a particular region of color space (e.g., for colors within the Blue quadrant of the FMH color circle) would also show increased Stroop interference for those trials in which the problematic color was either visually presented or referred to by the word (e.g., BLUE-yellow, YELLOW-blue, BLUE-red, RED-blue, etc.). In order to test this hypothesis, we first identified those participants who had a FMH error score greater than 2 SDs from the mean of all participants for colors within each quadrant (i.e., each of the four sets of color caps) of the FMH test. We then computed, for each of these individuals, the Stroop strength (incongruent mean RTs minus Congruent mean RTs) for all trials that included that color, either as the word's ink or as the word's name (or both for congruent trials). Table 1 shows the color-specific mean Stroop strengths of each group of participants with abnormal color vision within a particular color quadrant: Stroop interference was in all cases greater than the mean of all participants; most importantly, the largest increase in Stroop

interference (about twofold) occurred for those conditions that included the color for which a group of participants had shown abnormal perception.

-----  
*Table 1 about here*  
-----

Experiment 1 B. In the previous experiment there were the same amount of congruent and incongruent trials (N= 48); that is, each congruent trial (e.g., BLUE in blue) was repeated 12 times. Moreover, there were more repetitions of individual color-word pairs in the “opponent” condition (for which there is only one possible incongruent pairing; e.g., BLUE in yellow) than in the “non-opponent” condition; in this way, both incongruent condition would have the same amount of trials (N= 24). This manner of pairing dimensions of colors and words to form a stimulus set typical of most Stroop research and, as Melara and Algom (2003, p. 442) point out, its popularity might stem from the investigators’ intention to balance the number of items in the congruent and incongruent conditions so that the equal frequency of stimuli in the two conditions will not be predictive of the color or vice versa. However, Melara and Algom have shown that this assumption is incorrect because the relatively low dimensional uncertainty of each congruent stimulus encourages participants to expect congruent matchings, which enhances congruent performance relative to incongruent performance. Jacoby and colleagues (2003) have also shown that the influence of word reading on Stroop color naming decreases as a function of test items that are incongruent.

The above reasoning can also be extended to the present study’s unequal repetitions of individual color-word pairs in the “opponent” condition than in the “non-opponent” condition. In fact, the suspicion arises that the reduced interference of the “opponent” trials compared to the “non-opponent” condition might result from the relatively lower uncertainty of each “opponent” incongruent stimulus relative to a “non-opponent” incongruent stimulus. Hence,

in order to dispel doubts that the “opponent” advantage was not simply due to the design that we had previously borrowed from the “typical” Stroop study, in Experiment 1B we performed again a single-trial computerized version of the classic color-word Stroop task, but the words paired to each color for the “opponent” and “non-opponent” incongruent matches were now equally predictive. In other words, each individual pair in the “opponent” condition (e.g., BLUE in yellow or RED in green) had the same number of repetitions (N= 9) that each individual pair (e.g., BLUE in red or RED in yellow) in the “non-opponent” condition. Moreover, each congruent color-word pair (e.g., RED in red) was also repeated for the same amount of trials (N= 9).

If the reduced Stroop interference for “opponent” color-words matches observed in Experiment 1A was simply due the unequal frequency of specific color-words combinations, then in the following experiment we should observe no difference in the size of the Stroop interference between the “opponent” and the “non-opponent” conditions. In addition, we should also observe a general decrease of Stroop interference, due to larger number of incongruent than congruent trials (cf. Jacoby et al., 2003).

## **Method**

Participants. 35 students (mean age = ??; SD= ?) at the University of Tromsø (?? females and ?? males) volunteered to participate in the new color-word Stroop experiment. None of these participants received the color vision tests.

Stimuli. These were the same used in the previous experiment.

Apparatus and Procedure. As in the previous experiment, the G, H, J, and K keys were relabeled with focal blue, green, red and yellow color patches. Only one sequence of the color patches was used in this experiment (from left to right): green, red, yellow, and blue (i.e., the GRYB set). The procedure was identical to the previous experiment. However, the total



number of trials was 144 and the frequency of each congruent color-word pair, incongruent “opponent” color-word pair, and incongruent “non-opponent” color-word pair was the same (N= 9). The trials presentation order was completely randomized by use of Superlab © software.

Results. We first calculated descriptive statistics for each participant, obtaining a mean response time (RT) for correct responses and error rate for each combination of the variables Word Color (i.e., blue, green, red, and yellow), Word Name (i.e., BLUE, GREEN, RED, and YELLOW). RTs from trials on which errors occurred were excluded from analyses of the RTs, and trials with RTs greater than 3 standard deviations (SDs) from each individual's mean RT for that cell were treated as outliers and excluded from all subsequent analyses.

We first performed a repeated-measures analysis of variance with Condition (Congruent, Opponent, Non-opponent) as the within-subject variable as the between-subjects factor and RTs as the dependent variable. There was a main effect of Condition,  $F(2,352) = 80.9, p < 0.0001$ . Participants evaluated the Congruent color-word pairs (mean RT= 758 ms; SD= 141) faster than Opponent pairs (RT= 810 ms; SD= 147), whereas Non-Opponent pairs were evaluated the slowest (mean RT= 848 ms; SD= 168). Separate ANOVAs confirmed that the differences were significant for each combination of conditions.

We also performed a repeated-measures analysis of variance with Condition (Congruent, Opponent, Non-opponent) as the within-subject variable as the between-subjects factor and mean % errors as the dependent variable. Error rates were low in all of the three conditions (Congruent: mean % error = 3.0, SD= 4.1; Opponent: mean % error = 3.4, SD= 3.7; Non-opponent: mean % error = 2.5, SD= 2.5) and there was no significant effect of Condition,  $F(2, 52) = 1.0, p < 0.38$ .

## *Discussion*

Despite the fact that each individual color-word match appeared equally often in Experiment 1B, this experiment replicated the reduced Stroop interference for “opponent” color-word pairs that we had observed in Experiment 1A. However, there was a reduction in the size of the Stroop effect between Experiment 1A (in the condition in that used the RGBY sequence of color-labeled keys; mean RT difference = 71 ms) and Experiment 1B (mean RT difference = 41 ms). Such a decrease in the influence of word reading on Stroop color selection is likely to be due to the asymmetry in the proportion of incongruent items in Experiment 1B, which had more incongruent (“opponent” and “non-opponent” combined) than congruent trials, versus the equal number of trials in the two conditions of Experiment 1A (cf., Jacoby et al., 2003; Lindsay & Jacoby, 1994; Melara & Algom, 2003; Tzelgov, Henik & Berger, 1992).

Nevertheless, it might not be surprising that the distance in similarity between the color dimension of the stimulus and the color dimension indicated by the word is a robust factor in Stroop interference and that this cannot be entirely accounted by differences in the conditional probability of words and their matching colors. In fact, Klopfer (1996) had already shown that color naming becomes increasingly difficult when colors and words refer to closer-by regions of the conceptual color space; and in Klopfer’s study the color words were all equally predictive of the colors of the stimuli (as the stimuli of Experiment 1B of the present study).

### *Experiment 2: Neural networks simulations.*

In this “experiment”, we made a few simple modifications to a well-known PDP model of the classic Stroop color-word task by Cohen, Dunbar, and McClelland (1990), so as to (grossly) implement human trichromacy. We expected that such a manipulation would be

sufficient to reproduce the reduced Stroop strength for opponent color-name pairs, relatively to non-opponent pairs. The basic architecture of the original model by Cohen and colleagues is displayed in Figure 3.

-----  
*Figure 3 about here*  
-----

Cohen et al.'s model has two processing pathways, one for processing color information, the other for processing word information. Both pathways converge on a common response mechanism. In each pathway there is an input layer, an intermediate layer, and an output layer. Also, there are two task demand units, which are used to model the allocation of attention to one or the other task (color naming or word reading). Processing occurs in the following way: Units at the input level are activated. Activation then feeds forward through the intermediate units and to the output units. A response occurs when the activation value of a response unit exceeds a certain threshold. Individual stimuli and responses have discrete, local representations in this model; that is, a single input unit in the color pathway, the word-reading pathway, and response pathway represents each ink color, color word, and response, respectively.

In order to simulate the experimental findings described above with opponent versus non-opponent color-word pairs, we introduced some modifications to Cohen and colleagues' (1990) model. First of all, we needed to represent more than just two colors. Secondly, in order to implement, albeit at a gross level, three types of retinal cones, which are maximally sensitive to different wavelengths of light (i.e., the "routine" trichromacy of most primate species; cf. SurrIDGE et al., 2003), we introduced distributed representations (where each unit in a given input or output layer contributes to the representation of all colors or color words) instead of the discrete, local representations (where one unit corresponds to one color or color

word) used by Cohen and colleagues. In other words, by coding ink colors as patterns of activation across different types of “cones” at the input layer, the network would encode similarities among colors in a biologically plausible fashion. We call this model the “Human Eye” model. The representations used in the current simulations are listed in Table 1 and the architecture of our slightly revised model is displayed in Figure 4.

-----

*Table 2 and Figure 4 about here*

-----

In this scheme, each of the three color input units of the network corresponds to one of the three types of cones; the leftmost to the short wavelength cones, the middle to the medium wavelength cones, and the rightmost to the long wavelength cones. The listed representations were chosen on the basis of the fact that red mostly engages the long wavelength cones, green mostly engages the medium wavelength cones, blue mostly engages the short wavelength cones and yellow engages medium and long wavelength cones to a roughly equal degree.

Training the network. Training was done in the same manner as with the original model, with a few minor changes. A backpropagation learning algorithm (Rumelhart, Hinton, & Williams, 1986) was used to produce the correct response to information in one of the two processing pathways. Thus training patterns consisted of input to one of the two task-demand units, as well as input to the corresponding pathway (see Table 3). Note that the training stimuli do not contain any instances of simultaneous ink color and color word inputs. This is meant to reflect the fact that people rarely see Stroop-like stimuli, except in experimental tasks.

-----

*Table 3 about here*

-----

When training started, the connection strengths of the network were all set at small random values. All connections strengths were modifiable by backpropagation, except for those between the task demand units and the intermediate units in their respective pathways. These strengths were frozen at +4.0, to offset a permanent bias of -4.0 applied to all intermediate units. Thus, when a training pattern was presented to one of the pathways, the input at the task demand unit effectively brought the activation of the intermediate units in the corresponding pathway up to 0.0, which is in the middle of their most dynamic range. This arrangement is similar to that in Cohen and colleagues' (1990) model and was meant to capture the effective filtering of an attentional mechanism. Similarly, we accepted their assumption that reading is a more automated process than color naming, so that 75% of all training patterns were color words, whereas only 25% of all training patterns were ink color inputs. Each training sweep consisted of three instances of each color word, and one instance of each ink color. We used a learning rate of 0.1 and a momentum of 0.0. Each instance of the model was trained for 50,000 sweeps, at which point the output units' activation very rarely deviated from the correct value by more than 0.2.

Another difference between the current model and that of Cohen and colleagues (1990) was that, in the original model, the activation value of a given unit was not based upon its instantaneous net input, but rather, on the net input averaged over time. In the current model, output activations are computed in a single step, and responses are evaluated on the basis of the root mean squared error (RMSE) of the output patterns. That is, a given output pattern of the model is compared to the desired output. The root of the mean of the squared deviations of such a comparison provides a measure of the model's performance. Hence, like other authors (e.g., Seidenberg & McClelland, 1989) we interpreted the size of the RMSE as our estimate of the latency of the model's response. Indeed, output activations computed in this way can be shown to correspond to the asymptotic activations in a cascaded network.

Simulation 1: The basic Stroop effects. The purpose of our model's first simulation was to see whether it was able to replicate the basic Stroop phenomena modeled by Cohen and colleagues (1990). Specifically: (i) that word reading is faster than color naming, (ii) that color naming is influenced by words, (iii) that word reading is not affected by ink color, and (iv) that there is less facilitation than interference. Fifty instances of the model were trained and the model was tested for word reading alone, color naming alone, and Stroop color naming. The RMSEs for each output pattern were then calculated and averaged across model instances. The model behaved in accordance with the basic original findings, displaying an advantage for word naming as well as the Stroop interference with incongruent pairs and facilitation effects with congruent ones.

Simulation 2: "Human Eye" (trichromatic input layer) Model: Reduced Stroop strength with opponent color-word pairs. The main goal was to simulate the attenuated Stroop interference, observed with human participants, when the color-word pairs were opponent colors as opposed to non-opponent colors. As expected, the interference effect was smaller when the incongruent colors were opponent colors, compared to when they were non-opponent colors. Each instance of the model (N= 50) was treated as a subject in an ANOVA with Condition (Congruent, Opponent, Non-opponent colors) as the "within-subject" factor and mean RMS error as the dependent variable. The analysis revealed a significant difference,  $F(2,49) = 385, p < .0001$ . Post-hoc Fisher's PLSD comparisons confirmed that each condition differed significantly from any other, Critical Difference = .024,  $.09 < \text{Mean Differences} < .33, p < .0001$ .

Simulation 3: "Alien Eye" (hyper-chromatic input layer) Model. In order to evaluate whether the attenuation of the interference effect obtained in the previous simulation was really due to the manipulation at the input layer, and not just a side effect of some other variation of Cohen et al.'s (1990) original model, we implemented an expanded version using

a localist representation scheme (i.e., one unit representing each color). The architecture of this expanded localist network is displayed in Figure 5. The ink color representation vectors used in the simulation were 0001, 0010, 0100, and 1000 for Red, Green, Blue, and Yellow, respectively.

-----  
*Figure 5 about here*  
-----

The network was then trained as before. Again, the RMS Errors were calculated and averaged across the fifty model instances for each condition. The model displayed the basic Stroop phenomena: facilitation for congruent colors and interference for non-congruent colors. Importantly, this model did not yield the reduced Stroop effect with opponent colors. Although, the same ANOVA (with instances of the model used as subjects), Condition (Congruent, Opponent, Non-opponent colors) as the “within-subject” factor, and mean RMS error rates as the dependent variable revealed a significant effect,  $F(2,49) = 385$ ,  $p < .0001$ , the post-hoc Fisher’s PLSD comparisons showed that the effect was entirely due to the Congruent condition being significantly different from both Incongruent conditions, Critical Difference = .012, Mean Differences = .11 and .12,  $p < .0001$ , with no difference between the Opponent and Non-opponent conditions (Mean Difference = .006).

Thus, we conclude that the effect of opponent pairs evident in the previous simulation derived from the similarity structure imposed by the specific organization of the input vectors. Figure 6 illustrates together the results of both Simulation 2 (trichromatic model) and Simulation 3 (hyperchromatic model).

-----  
*Figure 6 about here*  
-----

### *General Discussion*

We found that 1) individual participants' differences in their color discrimination abilities influenced their performance in the classic Stroop color-word task; 2) this was also reflected in the effect of sex of the participants on both color vision and Stroop interference; 3) color-word pairs with opponent colors reduced the strength of Stroop interference (i.e. the difference in RTs with their corresponding congruent trials) compared to non-opponent color-name pairs; 4) the reduced strength of Stroop interference with opponent colors is robust and the effect remains strong when the conditional probabilities of words matching specific colors are made equal; 5) vocal and manual responses led to different Stroop interference: the strongest with verbal responses and the weakest when matching key presses to color patches with opponent colors adjacent to one another.

The association between individual differences in color vision and Stroop performance is of particular interest and underlines a fundamental factor of the Stroop effect. Indeed, the present results point to the need of incorporating sensory input factors from the color system within a complete account of the Stroop effect. One way to conceptualize the influence of sensory input factors is to posit that individual differences in sensory discriminations change the "landscape" of color space. That is, if the color (e.g., green) and the word (naming a different color, e.g., BLUE) activate different regions in color space, these regions might differ between individuals, both in extent and overlap. Hence, the word blue would interfere to a lesser degree in individuals who are able to discriminate well blue from green than in individuals who make poor discriminations between these two colors. This hypothesis was supported by the positive relationship between susceptibility to Stroop interference and the error rates in a color discrimination task. In addition, it was found that individuals with deficient discriminations of adjacent colors (e.g., blue-green) were more susceptible to Stroop interference when the color and the word matched within the deficient range of the color



spectrum than participants who were not deficient at discriminations of the same range of colors.

These findings suggest that interference can be determined at an “early” selection stage, i.e. the perceptual encoding stage of the ink-color information. This aspect is perhaps made more explicit by the neural network simulations. In such simulations, we introduced a (coarse) “biologically plausible” modification of a well-developed model of the Stroop effect (i.e., Cohen et al., 1990; cf. O’Reilly & Munakata, 2000), so that the encoding vector or input layer would code ink colors as patterns of activation across different types of “cones”. First of all, it was found that such a simple change at the level of the input layer was sufficient in simulating the reduced Stroop interference observed with human participants. The “Human Eye” or “trichromatic” model showed a significant difference between incongruent color-word pairs involving opponent colors as opposed to incongruent color-word pairs involving non-opponent relations. Interestingly, only this distributed trichromatic input layer appeared responsible for generating the difference in effect magnitude for opponent and non-opponent color-word pairs. The lack of a difference in interference between types of incongruent color-word pairs for the “Alien Eye” or “hyperchromatic” model strengthens the interpretation that organization at the encoding stage is sufficient for the emergence of similarity effects on Stroop performance. Note that, according to the model, the color and the word pathways in the model do not meet until the response level of the model; therefore the differences in effect magnitudes between opponent and non-opponent pairs in these simulations can be attributed entirely to the processing of physical color. Thus, the difference between the two levels of interference appears to reflect the similarity structure imposed at the color encoding stage (i.e., the amount of scalars shared) of the “trichromatic” model.

We surmise that individual differences in sensory discriminations (e.g. genetically based variations) are likely to shape different color spaces. In multidimensional scaling

studies, color-deficient individuals yield, in color matching task, a “degenerate” version of Newton’s color circle with the deficient sides of the circle collapsed together (Shepard & Cooper, 1992; Shepard, 1997). In other words, for different individuals, the color and the word might activate regions of color space of differing extent and degree of overlap. In turn, the use of color labels will be influenced by such differences among individuals of colors’ proximity within each color space. For example, a person with difficulty in discriminating different shades in one region of the spectrum would be expected to be more prone to use (wrongly) the name of an adjacent hue. This would also lead to increased “lexical competition” (cf. MacWhinney, 1987), that is increased applicability of other terms in the lexicon than the target one. In the color-word Stroop, an increase in perceptual difficulty would result in increased interference when such an alternative, potentially applicable, name is provided by the word stimulus. Thus, one proposal is that “early” perceptual processing might produce its effects by “cascading” onto processes that influence access to color semantics and the production of color labels. As perceptual encoding begins, information flows directly or cascades onto the subsequent levels, affecting later processing. Importantly, increased difficulty of encoding will have ‘knock on’ effects, transmitted up the system from one level to the next, which reveal themselves as a strong source of interference.

Nevertheless, one major source of interference in color-word Stroop has been taken to occur at a conceptual level (Klein, 1964; Scheibe et al., 1967; Seymour, 1977; Stirling, 1979; Klopfer, 1996; Luo, 1999). Several studies have shown that the difficulty in naming color increases directly with the semantic proximity of the words in which the colors were printed. Klein (1964) was the first to show the phenomenon that distantly related color names produced a decrease in Stroop interference than closely related color names. In addition, common words that did not name colors caused a further decrease in interference, but words that named object implying specific colors (e.g., lemon, sky) caused a smaller decrease in

interference than words without such associations (e.g., friend) or rare words and nonsense syllables. Interestingly, Klein also proposed that semantic relatedness modulates the “attention-catching” power of the word; the greater the competition between the color concept activated by the word and the color itself, the more the subject needs to perceptually re-sample the color (in Klein’s words, p. 585: “S restimulates himself with the color of word-color combination”). Thus, in Klein’s view, it would be the seeking of additional perceptual input from the color that would then result in a lengthening of RTs. More recently, Klopfer (1996) has shown that Stroop interference is not the same for all incongruent color-word pair (e.g., the interference obtained with PURPLE when the color of the word is yellow is less than the interference with PURPLE in blue). Klopfer pictures this process as both the color and the word (naming a different color) activating two regions within a color conceptual space. Distance in color conceptual space and degree of overlap between such regions will determine the extent of processing (e.g., selective attention) needed to discriminate between the two. Near neighbors in color space will be then related to increased performance time.

One of the other findings of our empirical study was that female participants evaluated color-word pairs faster than the males and showed less Stroop interference. Given that the female participants had overall better color vision than the males (a common finding in large samples of subjects; e.g. Pickford, 1951), it seems consistent that females were also faster than the males. However, in his thorough review of the literature on Stroop effect, MacLeod (1991, p. 184) concluded: “There are no sex differences in Stroop interference at any age”. Given the present results, we tend to agree with the beginning of MacLeod’s next sentence in the article: “Perhaps this is too strong”.

Modulatory effects of response types on Stroop performance have been described in various studies (e.g., White, 1969; Logan & Zbrodoff, 1998; Henik et al., 1999), in particular the fact that vocal responses lead to a stronger Stroop than color matching with key responses

(e.g., McClain, 1983; Durgin, 2000). As pointed out by Besner (2001), there is now clear evidence of semantic level involvement in Stroop tasks also with manual responses.

Nevertheless, we cannot exclude, as pointed out by Dalrymple-Alford and Azkoul, (1972) that Stroop effects with manual responding reflect the mediation of subvocal color-naming and would disappear with sufficient trials. Moreover, one of the interesting results of the present study was that different manual responses led to different Stroop interference: the strongest with the RBGY mapping and the weakest with the GRYB mapping (i.e., when matching key presses to color patches with opponent colors adjacent to one another). Note that adjacent keys map onto points of the color circle that are an average of 150 degrees apart in the GRYB mapping (green-to-red = 180 degrees apart, red-to-yellow = 90 degrees, yellow-to-blue = 180) whereas with the RBGY mapping the difference between adjacent keys is 90 degrees. Hence, this effect may be another example of the pervasive effect of conceptual proximity on Stroop interference. Remarkably, it seems that such influence might occur at a rather implicit level of processing, since it seems unlikely that the typical subject is using an explicit knowledge that green-red and yellow-blue are on opposite sides of the color circle.

Among the non-significant findings, it was surprising that the error rates with the Ishihara Plates did not correlate significantly with Stroop interference since 1) FMH error rates and Ishihara error rates were correlated and 2) a study of van Boxtel and colleagues (2001) using the (clinical) cards version of the Stroop test had shown that red/green color weakness led to slower color naming. Nevertheless, there was a tendency for a positive correlation with Ishihara errors and Stroop. To conclude, the FMH test may have better predictive power than the Ishihara test for RTs measurements on other color-related tasks. Future studies could assess in more detail the effects of specific color impairments on Stroop interference. For instance, color-deficient participants who are missing the middle-wavelength (M) cone would have problems discriminating the red from the green opponent color as well

as discriminating these from the intermediate non-opponent colors in the yellow-orange range. We would then expect to observe in such participants not only an increased Stroop interference compared to non-deficient subjects but also a reduced difference between incongruent non-opponent Stroop interference and incongruent opponent Stroop interference. Future simulations may implement even more biologically plausible constraints than the simple one we used here. For example, color opponency (i.e., “L-M” and “S-(L+M)” mechanisms) may have cascade effects that are somewhat different and their study could further refine the predictive power of the models. Thus, if red and green inhibit each other early in visual system (i.e., early at the retinal ganglion cells level as well as later at the cortical level, De Valois & De Valois, 1993; Engel, 1999), the ‘knock on’ effects of such inhibitory effects should be measurable in the production of a color label in a Stroop task.

### *Acknowledgments*

We thank Ernest Dalrymple-Alford and Dale Kopfler for their insightful comments on drafts of this manuscript. We are also very grateful, for their help in data collection and in discussions of the project, to: Yngvild Arnesen, Guro Brandvik, Camilla Breivik, Thomas Espeseth, Toril Fossmo, Knut Hansson, Olav Kandel, Kjetil Karstad, Cecilie Larsen, Kathrine Rasch, Eline Røed, Oddrun Vermeer, Synnøve Simonsen, Jill Terres, Marianne Voldnes, and Kenneth Øvervoll.

## References

- Besner, D. (2001). The myth of ballistic processing: Evidence from Stroop's paradigm. *Psychonomic Bulletin & Review*, **8**, 324-330.
- Brown, T.L., Gore, C.L., and Carr, T.H. (2002). Visual attention and word recognition in Stroop color naming: Is word recognition "automatic"? *Journal of Experimental Psychology: General*, **131**, 220-240.
- Cohen, J.D., Dunbar, K., and McClelland, J.L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, **97**, 332-361.
- Cohen, J.D., Usher, M., and McClelland, J.L. (1998). A PDF approach to set size effects within the Stroop task: Reply to Kanne, Balota, Spieler, and Faust (1998). *Psychological Review*, **105**, 188-194.
- Dalrymple-Alford, E.C. (1972). Associative facilitation and interference in the Stroop color-word task. *Perception & Psychophysics*, **11**, 274-276.
- Dalrymple-Alford, E.C., and Azkoul, J.(1972). The locus of interference in the Stroop and related tasks. *Perception & Psychophysics*, **11**, 385-388.
- De Valois, R.L., and De Valois, K.K. (1997). Neural coding of color. In A. Byrne and D.R. Hilbert (eds.), *Readings on color, Volume 2: The science of color*, pp.93-140. Cambridge, MA: The MIT Press.
- Durgin, F.H. (2000). The reverse Stroop effect. *Psychonomic Bulletin & Review*, **7**, 121-125.
- Dyer, F.N. (1973). The Stroop phenomenon and its use in the study of perceptual, cognitive, and response processes. *Memory & Cognition*, **1**, 106-120.

Engel, S.A. (1999). Using neuroimaging to measure mental representations: Finding color-opponent neurons in visual cortex. *Current Directions in Psychological Science*, **8**, 23-27.

Glaser, W.R., and Glaser, M.O. (1993). Colors as properties: Stroop-like effects between objects and their colors. In G. Strube and K.F. Wender (Eds.), *The cognitive psychology of knowledge*, pp. 1-32. Elsevier Science Publishers, B.V.

Henik, A., Ro, T., Merrill, D., Rafal, R., Safadi, Z. (1999). Interactions between color and word processing in a flanker task. *Journal of Experimental Psychology: Human Perception and Performance*, **25**, 198-209.

Hintzman, D.L., Carre, F.A., Eskridge, V.L., Owens, A.M., Shaff, S.S., and Sparks, M.E. (1972). "Stroop" effect: input or output phenomenon. *Journal of Experimental Psychology*, **95**, 458-459.

Hock, H.S., and Egeth, H. (1970). Verbal interference with encoding in a perceptual classification task. *Journal of Experimental Psychology*, **83**, 299-303.

Jacoby, L.L., Lindsay, D.S., and Hessels, S. (2003). Item-specific control of automatic processes: Stroop process dissociations. *Psychonomic Bulletin & Review*, **10**, 638-644.

Jensen, A.R., and Rohwer Jr., W.D. (1966). The Stroop color-word test: A review. *Acta Psychologica*, **25**, 36-93.

Kahneman, D., and Chajczyk, D. (1983). Tests of the automacity of reading: Dilution of Stroop effects by color-irrelevant stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, **9**, 497-509.

Kane, M.J., and Engle, R.W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, **132**, 47-70.



Kello, C.T., Plaut, D.C., and MacWhinney, B. (2000). The task dependence of staged versus cascaded processing: An empirical and computational study of Stroop interference in speech production. *Journal of Experimental Psychology: General*, **129**, 340-360.

Klein, G.S. (1964). Semantic power measured through the interference of words with color-naming. *American Journal of Psychology*, **77**, 576-588.

Klopfer, D.S. (1996). Stroop interference and color-word similarity. *Psychological Science*, **7**, 150-157.

Kornblum, S., Stevens, G.T, Whipple, A., and Requin, J (1998). The effects of irrelevant stimuli: The time course of stimulus-stimulus and stimulus-response consistency effects with Stroop-like stimuli, Simon-like tasks, and their factorial combinations. *Journal of Experimental Psychology: Human Perception and Performance*, **25**, 688-714.

Lindsay, D.S., and Jacoby, L.L. (1994). Stroop process dissociations: The relationship between facilitation and interference. *Journal of Experimental Psychology: Human Perception and Performance*, **20**, 219-234.

Logan, G.D., and Zbrodoff, N.J. (1998). Stroop-type interference: Congruity effects in color naming with typewritten responses. *Journal of Experimental Psychology: Human Perception and Performance*, **24**, 978-992.

Lu, C.-H., and Proctor, R.W. (2001). Influence of irrelevant information on human performance: Effects of S-R association strength and relative timing. *The Quarterly Journal of Experimental Psychology*, **54A**, 95-136.

Luo, C.R. (1999). Semantic competition as the basis of Stroop interference: Evidence from color-word matching tasks. *Psychological Science*, **10**, 35-40.

Mantere, K., Parkkinen, J., Mäntyjärvi, M., and Jasskelainen, T. (1995). Eigenvector interpretation of the Farnsworth- Munsell 100-hue test. *Journal of the Optical Society of America*, **12**, 2237-2243.

MacLeod, C.M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, **109**, 163-203.

MacWhinney, B. (1987). The competition model. In B. MacWhinney (Ed.), *Mechanisms of language acquisition* (pp. 249-308). Hillsdale, NJ: Erlbaum.

McClain, L. (1983). Effects of response type and set size on Stroop color-word performance. *Perceptual and Motor Skills*, **56**, 735-743.

Melara, R.D., and Algom, D. (2003). Driven by information: A tectonic theory of Stroop effects. *Psychological Review*, **110**, 422-471.

O'Reilly, R.C., & Munakata, Y. (2000). *Computational explorations in cognitive neuroscience: Understanding the mind by simulating the brain*. Cambridge, MA: The MIT Press.

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

Pickford, R.W. (1951). *Individual differences in colour vision*. London: Routledge and Kegan Paul LTD.

Roelofs, A. (2003). Goal-referenced selection of verbal action: Modeling attentional control in the Stroop task. *Psychological Review*, **110**, 88-125.

Rumelhart, D.E., Hinton, G.E., & McClelland, J.L. (1986). Learning internal representations by error propagation. In D.E. Rumelhart, J.L. McClelland, & the PSP Research Group (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition* (Vol. 1, pp. 45-76). Cambridge, MA: MIT Press.

Salo, R., Henik, A., and Robertson, L.C. (2001). Interpreting Stroop interference: An analysis of differences between task versions. *Neuropsychology*, **15**, 462-471.

Scheibe, K.E., Shaver, P.R., and Carrier, S.C. (1967). Color association values and response interference on variants of the Stroop test. *Acta Psychologica*, **26**, 286-295.

Seidenberg, M.S., and McClelland, J.L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review*, **96**, 523-568.

Shepard, R.N. (1997). The perceptual organization of colors: An adaptation to regularities of the terrestrial world? In A. Byrne and D.R. Hilbert (eds.), *Readings on color, Volume 2: The science of color*, pp.311-356. Cambridge, MA: The MIT Press.

Shepard, R.N., and Cooper, L.A. (1992). Representations of colors in the blind, color-blind, and normally sighted. *Psychological Science*, **3**, 97-104.

Sichel, J.L., and Chandler, K.A. (1969). The color-word interference test: The effects of varied color-word combinations upon verbal response latency. *The Journal of Psychology*, **72**, 219-231.

Stroop, J.R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, **28**, 643-661.

Stirling, N. (1979). Stroop interference: an input and output phenomenon. *Quarterly Journal of Experimental Psychology*, **31**, 121-132.

SurrIDGE, A.K., Osorio, D., and Mundy, N.I. (2003). Evolution and selection of trichromatic vision in primates. *TRENDS in Ecology and Evolution*, **18**, 198-205.

Tzelgov, J., Henik, A., and Berger, J. (1992). Controlling Stroop effects by manipulating expectations for color words. *Memory & Cognition*, **20**, 727-735.

van Boxtel, M.P.J., ten Tusscher, M.P.M., Metsemakers, J.F.M., Willems, B, and Jolles, J. (2001). Visual determinants of reduced performance on the Stroop color-word test in normal aging individuals. *Journal of Clinical and Experimental Neuropsychology*, **23**, 620-627.

White, B.W. (1969). Interference in identifying attributes and attribute names. *Perception & Psychophysics*, **6**, 166-168.

Yee, P.L., and Hunt, E. (1991). Individual differences in Stroop dilution: Tests of the attention-capture hypothesis. *Journal of Experimental Psychology: Human Perception and Performance*, **17**, 715-725.

Zhang, H., and Kornblum, S. (1998). The effects of stimulus-response mapping and irrelevant stimulus-response and stimulus-stimulus overlap in four-choice Stroop tasks with single-carrier stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, **24**, 3-19.

Zhang, H., Zhang, J., and Kornblum, S. (1998). A parallel distributed processing model of stimulus-stimulus and stimulus-response compatibility. *Cognitive Psychology*, **38**, 386-432.

Figure 1. Means (symbols) and SEs (bars) of response times (RTs) to color-word pairs (Congruent, Incongruent opponent, Incongruent non-opponent) when matching a color patch labeled on computer keys in two different orderings (i.e., Keys G-R-Y-B; Keys R-B-G-Y) and by naming aloud the color (i.e., microphone).

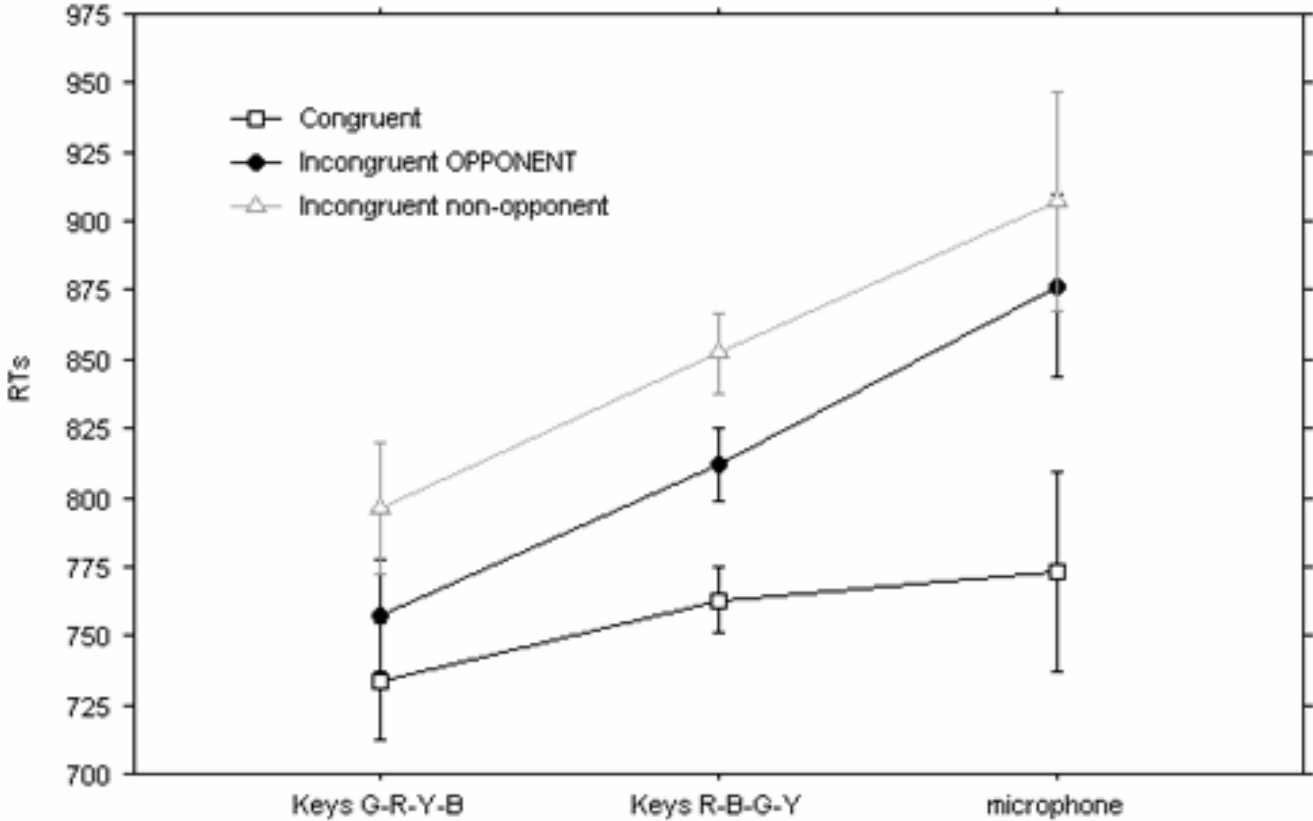


Figure 2. Means (symbols) and SEs (bars) of RTs to all pairs of color-word combinations.

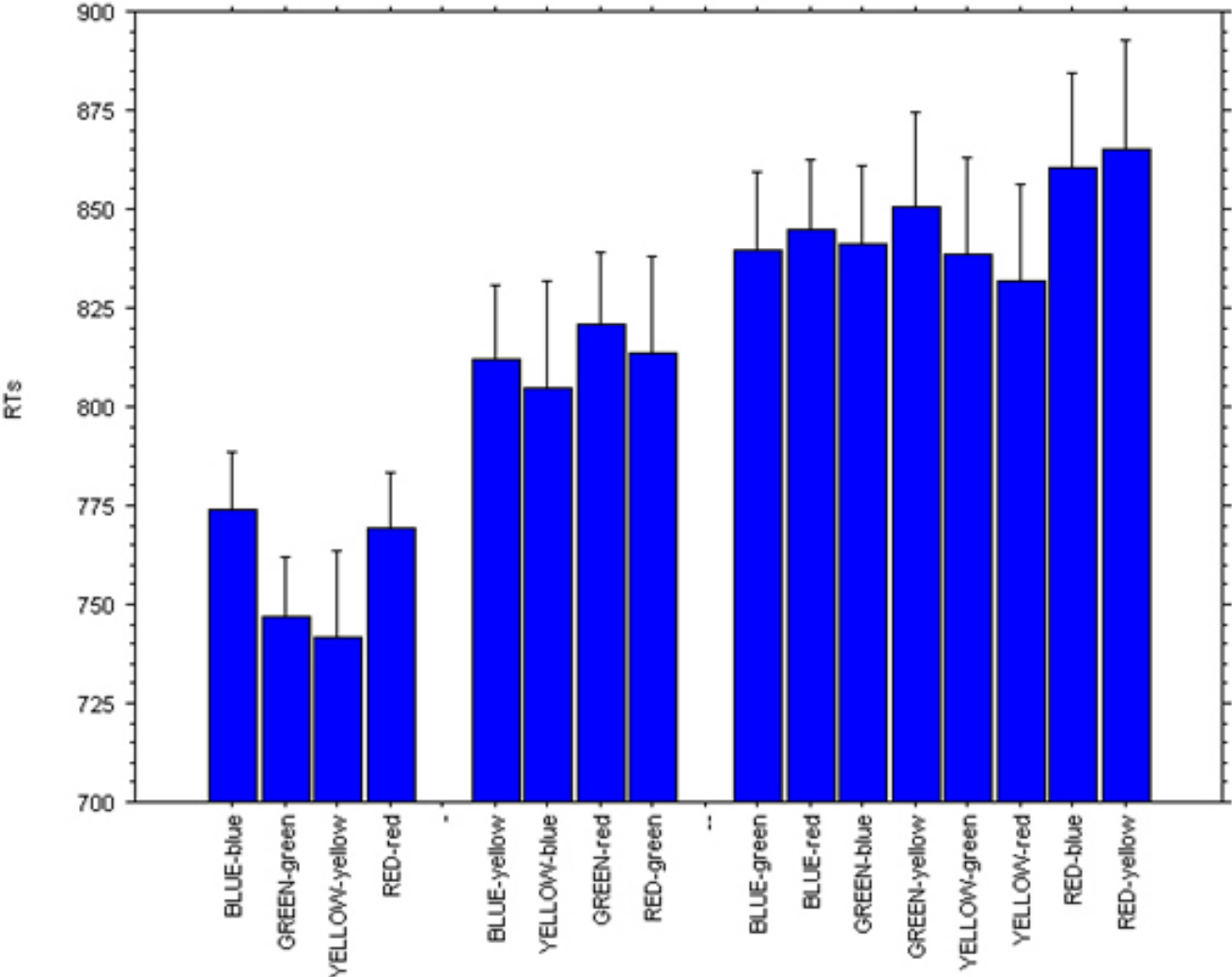


Figure 3. Regression plot of individual differences in color vision, as measured by FMH error scores, and the Stroop effect (i.e., the difference between all the color-word incongruent trials and the congruent trials).

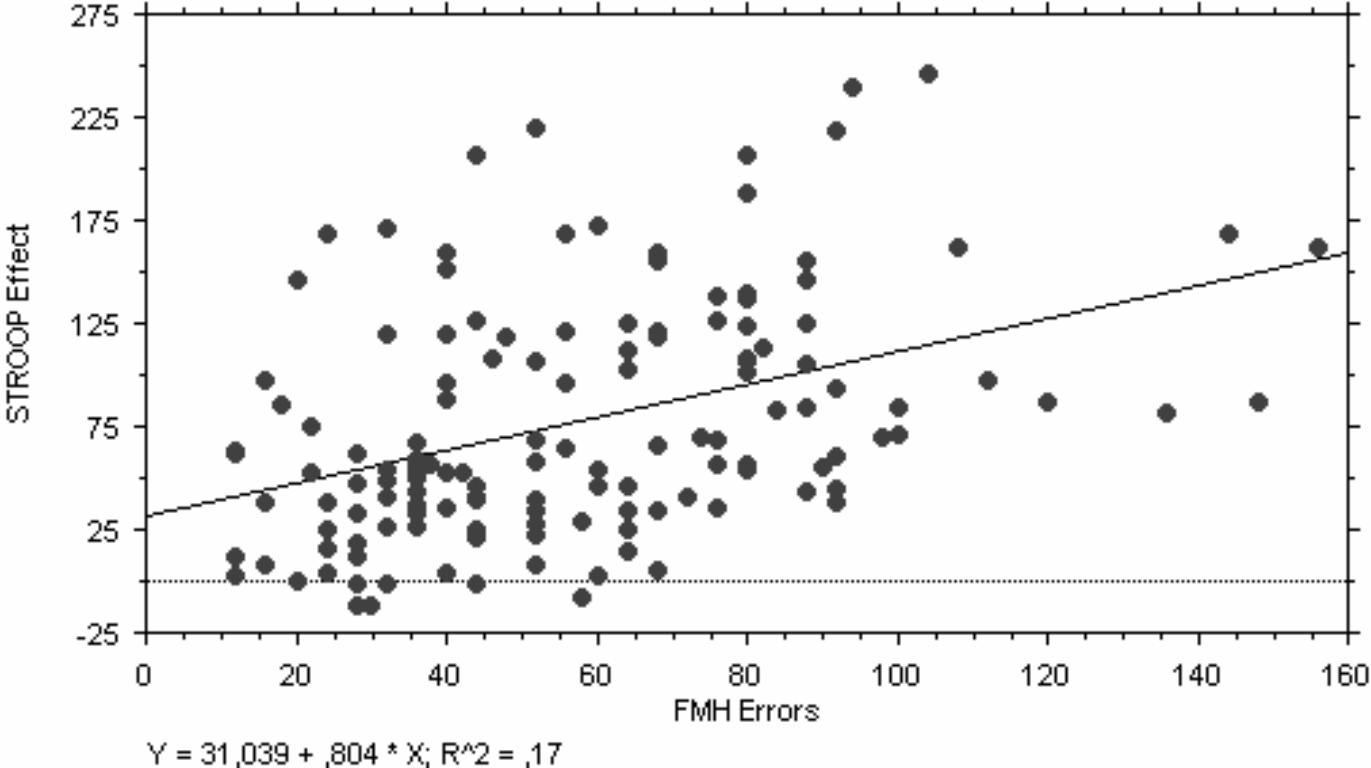


Figure 5. The architecture of the original connectionist model of Stroop performance of Cohen, Dunbar and McClelland (1990).

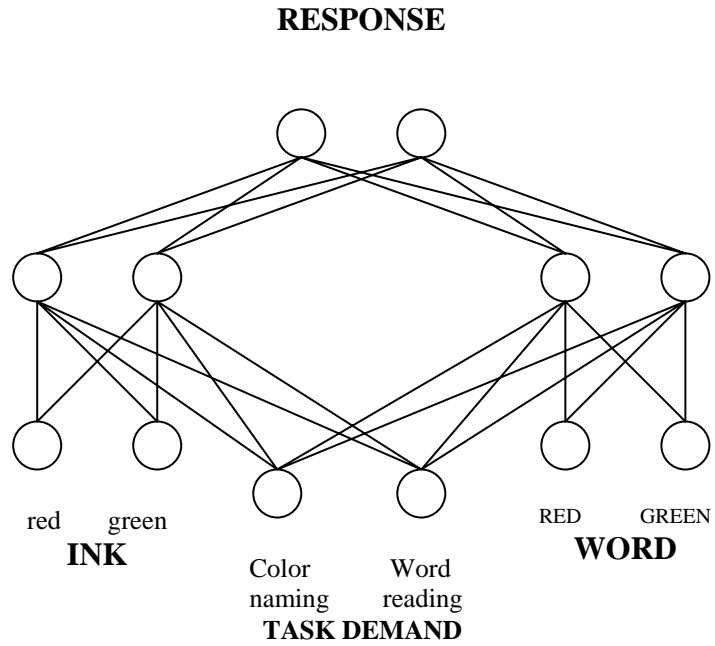




Figure 6. The architecture of the current “trichromatic” model.

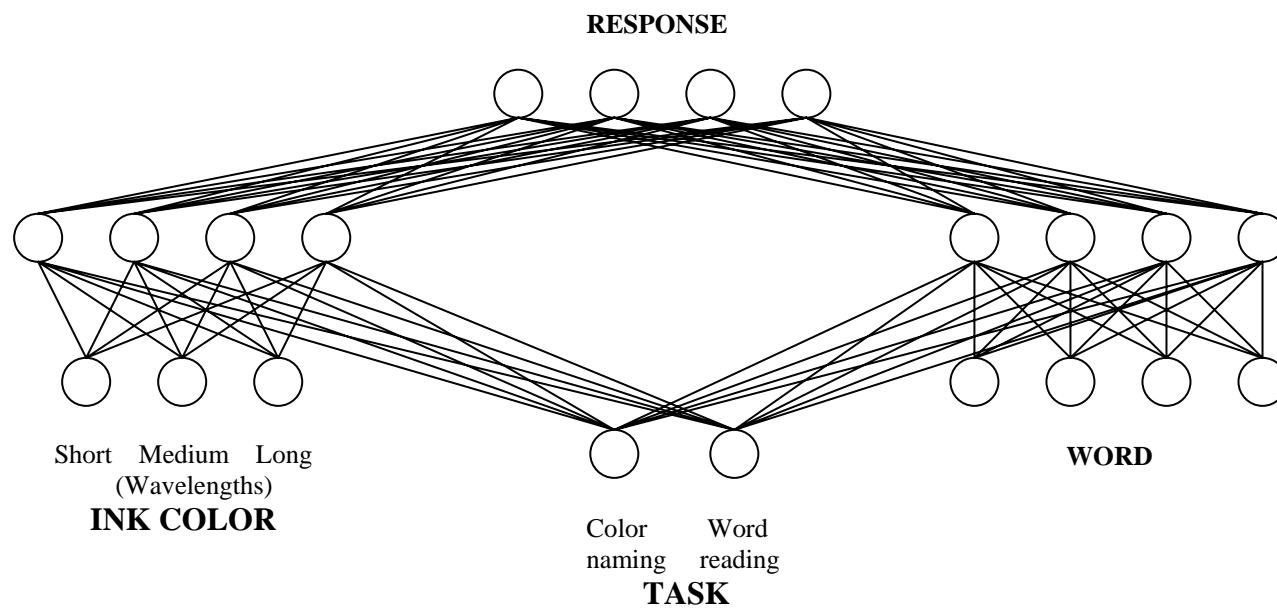


Figure 7. The architecture of the “hyperchromatic” version of the Cohen et al. (1990) model.

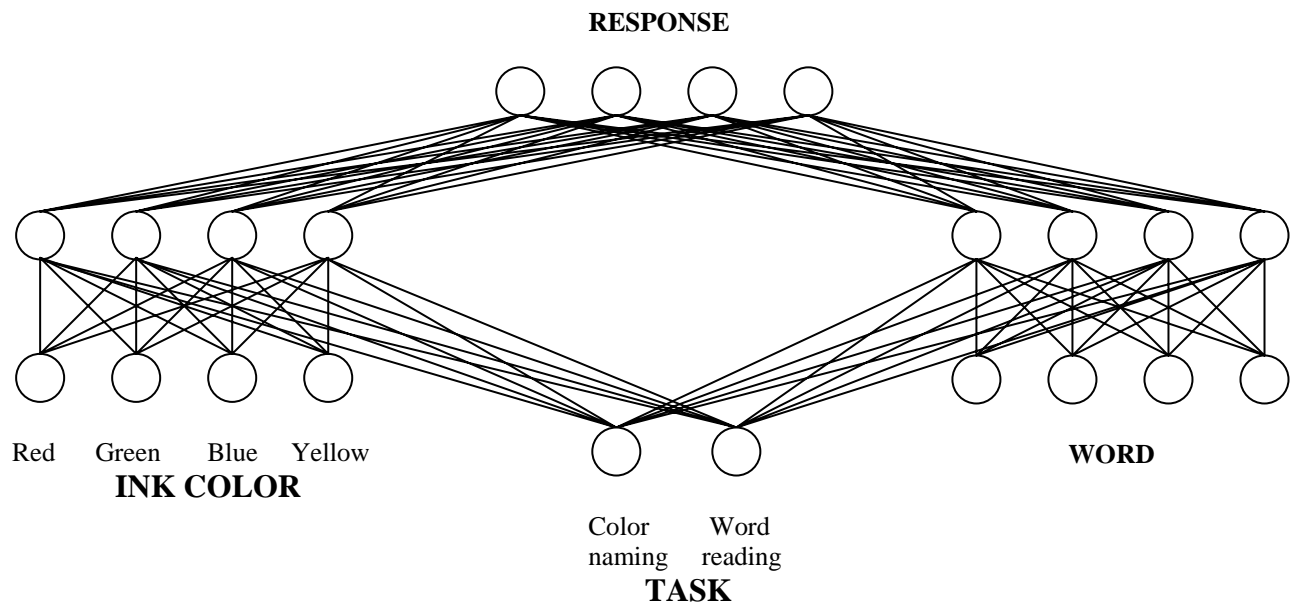


Figure 8. Root Mean Square (RMS) Errors (Standard Errors as bars) of Simulation 2 or “Alien Eye” (hatched columns) and Simulation 3 or “Human Eye” (filled columns).

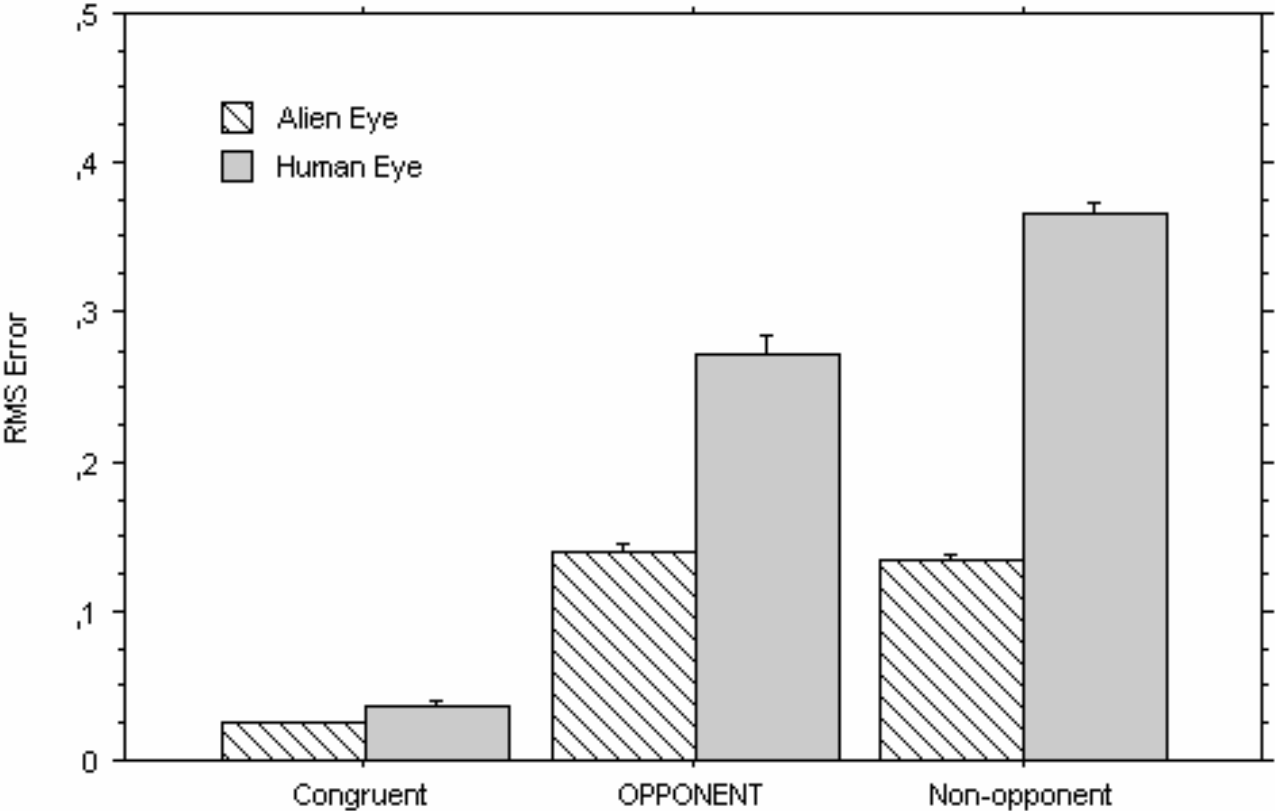


Table 1. Averaged Stroop effect, for trials in which red, yellow, green or blue, appeared as one of the four colors or color terms, in individuals with FMH error scores greater than 2 SDs from the mean scores of all participants for each color quadrant (red, yellow, green or blue) of the FMH color circle.

| <i>Participants</i>          | <i>RED</i>  |            | <i>YELLOW</i> |            | <i>GREEN</i> |            | <i>BLUE</i> |            |
|------------------------------|-------------|------------|---------------|------------|--------------|------------|-------------|------------|
|                              | <i>Word</i> | <i>Ink</i> | <i>Word</i>   | <i>Ink</i> | <i>Word</i>  | <i>Ink</i> | <i>Word</i> | <i>Ink</i> |
| RED deficient<br>(N= 9)      | 109         | 126        | 77            | 91         | 69           | 72         | 80          | 92         |
| YELLOW<br>deficient<br>(N=7) | 62          | 75         | 121           | 132        | 72           | 60         | 81          | 89         |
| GREEN deficient<br>(N= 11)   | 79          | 93         | 80            | 81         | 112          | 155        | 67          | 90         |
| BLUE deficient<br>(N= 12)    | 68          | 75         | 71            | 75         | 80           | 95         | 115         | 168        |
| All Participants             | 83          | 69         | 60            | 68         | 67           | 83         | 78          | 58         |

Table 2. *Representations used in the trichromatic Stroop model.*

|                 | Vector  |
|-----------------|---------|
| Color input     |         |
| Red ink         | 0 0 1   |
| Green ink       | 0 1 0   |
| Blue ink        | 1 0 0   |
| Yellow ink      | 0 1 1   |
| Word input      |         |
| "Red"           | 1 0 0 0 |
| "Green"         | 0 1 0 0 |
| "Blue"          | 0 0 1 0 |
| "Yellow"        | 0 0 0 1 |
| Response output |         |
| "Red"           | 1 0 0 0 |
| "Green"         | 0 1 0 0 |
| "Blue"          | 0 0 1 0 |
| "Yellow"        | 0 0 0 1 |

Table 3. Training Stimuli

| Task demand  | Color input | Word input | Response |
|--------------|-------------|------------|----------|
| Color naming | red         | -          | "red"    |
| Color naming | green       | -          | "green"  |
| Color naming | blue        | -          | "blue"   |
| Color naming | yellow      | -          | "yellow" |
| Word reading | -           | RED        | "red"    |
| Word reading | -           | GREEN      | "green"  |
| Word reading | -           | BLUE       | "blue"   |
| Word reading | -           | YELLOW     | "yellow" |

*Note.* Dashes indicate there was no input