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Transitions between color categories mapped with a reverse Stroop task

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Abstract

In the reverse Stroop task, observers are instructed to ignore the ink color in which a color word is printed (the distractor color) and to respond to the meaning of the color word (the target). Reaction times (RTs) are faster with congruent combinations when the ink color matches the word than with incongruent combinations when the ink color does not match the word. We manipulated the distracting ink color from congruent to incongruent and measured the transition from facilitation to interference. In Experiment 1, we confirmed that this transition could be assessed independently from the contextual influence of particular sets of stimuli and responses, implying that the color space in which interference and facilitation occurs is generalizable. In Experiment 2, we obtained reverse Stroop data for transitions between red and yellow, yellow and green, green and blue, and blue and red, and compared them with independent estimates of color appearance obtained by hue scaling for the same chromaticity samples. We find that the magnitude of the reverse Stroop effect can provide a reliable index of the similarity of color appearance between the distracting chromaticity and the color category represented by the target color word. Moreover, it will allow us to quantify the mapping between the chromaticity space defined at the cone photoreceptors and a cognitive color space defined at an advanced level of neural processing.

Keywords: Reverse Stroop, color categories, hue scaling, reaction times, color space

Introduction

The classic Stroop effect is the tendency for printed words to interfere with the verbal naming of colors (Stroop, 1935). Reaction time (RT) to name the ink color is longer if the printed stimulus is an incongruent color word (e.g. yellow ink and the word RED) than if the printed stimulus is neutral, with no color meaning (e.g. yellow ink and a string of Xs). Interference is generally defined as the difference between RTs for the incongruent and neutral conditions. Conversely, facilitation is the decrease in RT that is observed when a color word is printed in the congruent color (e.g. red ink and the word RED). Stroop effects are typically measured with primary colors (for review, see MacLeod, 1991), and the tuning in color space of the interference and facilitation effects is largely unknown. Potentially, the Stroop effect may provide a method of mapping the relationship between the chromaticity space defined at the cone photoreceptors and the cognitive space in which alternative representations of color interfere. In particular, it may reveal whether boundaries between the colors in this hypothetical cognitive space are continuous, like the cone space, or discrete; fixed or dynamic. We propose to use Stroop interference to investigate the properties of cognitive color space.

The tuning of the color representations underlying the Stroop effect, however, cannot be measured directly. Words for colors are necessarily categorical, and the manipulation of the ink color of the printed word will make the correct verbal response ambiguous. This limitation can be overcome by turning the task around and measuring instead the tendency for ink color to interfere with reading. This "reverse" Stroop task requires selective attention for the target word, with ink color being ignored (see Stroop, 1935, Experiments 1 and 3). With verbal responses, the reverse Stroop effect is typically much smaller than the Stroop effect, but Durgin (2000, 2003) has shown that large facilitation and interference effects can be measured using a set of colored response patches from which observers are required to select manually the appropriately colored patch. In the reverse Stroop task, the correct response to the color word remains unambiguous, while the ink color of the printed word can be varied along continua in color space, thereby allowing us to estimate the tuning of the underlying color representations.

Like the Stroop effect, the reverse Stroop effect involves interference between lexical and sensory representations of color. The conflict is thought to occur late in processing (MacLeod, 1991)—perhaps at a central response stage (Dyer, 1973) or even at a

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conceptual level of encoding (Seymour, 1977)—where the sensory representation of color is undergoing or has undergone a transformation from opponent color organization (e.g. Hering, 1920; Hurvich & Jameson, 1957) into categorical color organization (e.g. Boynton & Olson, 1990). The tuning of cognitive color categories has largely been explored by subjective hue scaling or naming procedures (e.g. Berlin & Kay, 1969; Abramov et al., 1990). However, the reverse Stroop effect, coupled with reaction-time techniques, offers a more objective approach to exploring the tuning and emergence of such color categories.

At one extreme, if reverse Stroop interference occurs at a stage in which color representation is completely categorical, then we might expect to find abrupt transitions from facilitation to interference: the distracting color will either fall inside or outside the target color category, and either facilitation or interference will result. If on the other hand, reverse Stroop interference occurs prior to categorical processing, or if color is never unequivocally categorized (e.g. if color "categories" are represented by distributed activity over several narrowly tuned color channels (e.g. Webster et al., 2002)), then we might expect to find gradual transitions from facilitation to interference.

In the experiments reported here, we set out to measure the tuning of the color representations underlying the reverse Stroop effect. Stroop and reverse Stroop effects are notoriously dependent on the sets of targets, distractors, and available responses (see MacLeod, 1991), and estimation of the magnitude of facilitation and interference depends critically on using the appropriate control condition (e.g. Lindsay & Jacoby, 1994). For these reasons, we first tested whether we could extract a measure of the color dependence of the reverse Stroop effect that was independent of the stimulus and response sets by comparing blocked and interleaved conditions. In the second experiment, we extended our study to include color transitions between the four unique hues arranged in spectral order, and we compared these reverse Stroop data with an assessment of color categories obtained *via* hue scaling.

Materials and methods

Stimulus presentation and data collection were computer controlled using a Cambridge Research Systems (Rochester, UK) VSG 2/5 Visual Stimulus Generator. Stimuli were presented on a calibrated cathode ray tube (CRT) (21″ Sony FD Trinitron), and observers responded using an analogue joystick. The timing of stimulus presentation and response acquisition was implemented using the ADC functionality of the VSG 2/5 and was therefore independent of the operating system on the host PC.

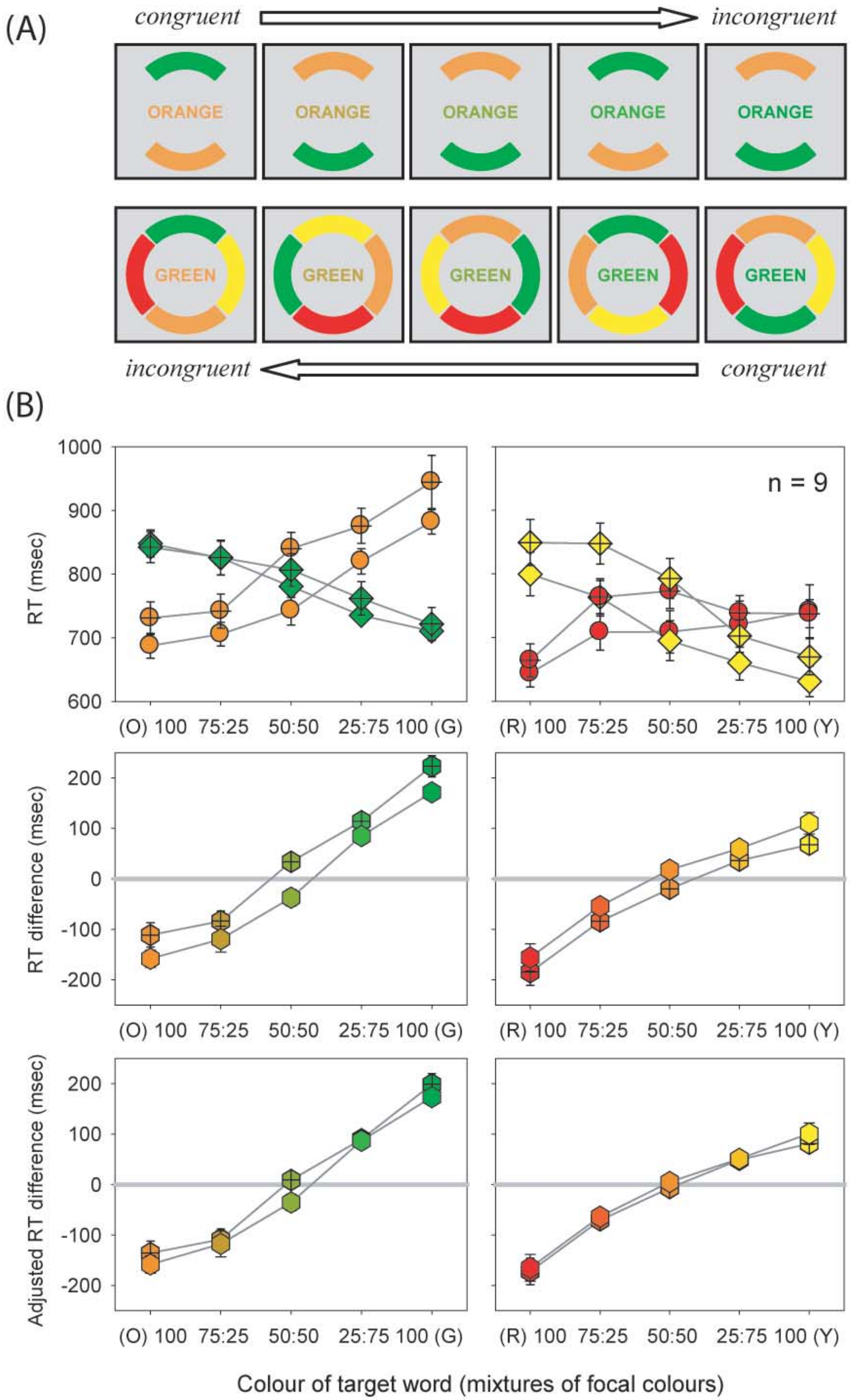
Table 1. *CIE 1931 (x, y) coordinates and luminance (cd/m^2) of the achromatic background and of the five focal colors used in this study*

	CIE x	CIE y	Luminance (cd/m^2)
Background	0.298	0.335	34.1
RED	0.622	0.346	13.8
ORANGE	0.538	0.413	37.2
YELLOW	0.423	0.505	65.5
GREEN	0.280	0.617	42.3
BLUE	0.152	0.076	6.9

We describe our stimuli using the following terms: (i) target word (the word requiring response), (ii) ink color (the chromaticity in which the target word is presented), and (iii) response patch (the region of the display to be selected for response). In preliminary experiments, we chose chromaticities that were the best or "focal" examples of each target word (see Table 1 for words and their CIE 1931 x, y coordinates and photopic luminances), and we set the response patches to these chromaticities. Intermediate ink colors were proportional color mixtures between pairs of focal colors.

Observers initiated each trial by using the joystick to move the cursor to within a small gray square set within an otherwise uniform display of mid-luminance white (CIE x, y coordinates: 0.298, 0.335; photopic luminance: 34.1 cd/m^2), which had previously been chosen to appear achromatic. The target word and response patches were presented (see Fig. 1A for examples), and the observer was required to move the cursor, as quickly as possible, to select the colored response patch that corresponded to the target word (a reverse Stroop task). Target words were presented in uppercase Arial font, and the height of letters subtended a visual angle of 1.0 deg at the viewing distance of 1 m. Target words were presented with a 200-ms ramped (raised-cosine) onset and remained visible until the observer responded. Response patches formed arcs that were equidistant (5.0 deg of visual angle) from the starting position of the cursor, and they were colored according to the set of target words. Each color of response patch was equally likely to occur in each position, and the colors were shuffled between trials. RT was measured for a ballistic movement of the cursor from the starting position to beyond the inner circumference of the correct response patch.

Fig. 1. (A) Representative stimuli for Experiment 1. Each gray box shows a possible combination of target word, ink color, and colored response patches. The top row shows the transition from congruent to incongruent for the target word ORANGE; the bottom row shows the same sequence of ink colors for the target word GREEN, in which the direction of congruency is reversed. Stimuli are from the ORANGE-GREEN blocked condition (top), with two response patches (orange and green), or from the ORANGE-GREEN interleaved condition (bottom), with four response patches (orange, green, red, and yellow). (B) Data for Experiment 1. Top row: Average RTs (nine observers) for correct responses to ORANGE (O, orange circles), GREEN (G, green diamonds), RED (R, red circles), or YELLOW (Y, yellow diamonds), in blocked presentations (filled-plain symbols) or interleaved presentations (filled-crossed symbols), as a function of ink color. Error bars show ±1 SE. Middle row: average RT differences (nine observers): [$RT_{ORANGE} - RT_{GREEN}$] and [$RT_{RED} - RT_{YELLOW}$] for blocked (filled-plain symbols) or interleaved (filled-crossed symbols). Symbols are color coded according to ink color. Bottom row: data from plots in the middle row adjusted vertically according to RTs measured in appropriate neutral conditions (i.e. RTs to respond to the word ORANGE, GREEN, RED, or YELLOW when displayed in black).


(A)
congruent
incongruent
ORANGE
ORANGE
ORANGE
ORANGE
ORANGE
GREEN
GREEN
GREEN
GREEN
GREEN
incongruent
congruent
(B)
n = 9
RT (msec)
RT difference (msec)
Adjusted RT difference (msec)
(O) 100 75:25 50:50 25:75 100 (G)
(R) 100 75:25 50:50 25:75 100 (Y)
Colour of target word (mixtures of focal colours)

Observers

Thirteen observers (aged between 20 and 62 years old) participated in these experiments. Five participated in both experiments, four in only Experiment 1, and four in only Experiment 2. All observers had normal color vision as assessed by the Ishihara plates, HHR pseudoisochromatic plates, and the Farnsworth-Munsell 100-Hue test. Four male and five female observers carried out Experiment 1, three of whom (H.E.S., S.K., L.T.S.) were well practiced on the task and were aware of the design and purpose of the experiment. The remaining six observers were naive and unpracticed. Four male and five female observers carried out Experiment 2, four of whom (H.E.S., S.K., L.T.S., and A.S.) were aware of the design and purpose of the experiment. One of the naive observers (M.D.) was experienced in making judgments of color.

Experiment 1: Blocked vs. interleaved presentation in reverse Stroop

We measured reverse Stroop interference as a function of the transition from congruent to incongruent combinations of word and ink color, as illustrated in Fig. 1A. In Experiment 1, we tested whether this transition could be measured independently of the contextual changes generated by varying the set of possible stimuli and responses. To do this, we considered two pairs of colors, (i) orange and green and (ii) red and yellow, and measured reverse Stroop interference for each pair of colors in pure blocks (containing only one pair) and in interleaved blocks (containing both pairs). For each pair, we used two appropriately colored response patches, and the two target words were presented in one of five possible ink colors: the two focal colors and three linear mixtures between them, for example, 100% orange; 75% orange + 25 % green; 50 % orange + 50% green; 25% green + 75% orange; 100% green. In pure blocks, there were two response patches, five possible distracting ink colors, and two possible target words (see Fig. 1A, top row). In interleaved blocks, there were four response patches, ten possible distracting ink colors, and four possible target words (see Fig. 1A, bottom row for examples).

We anticipated that the presence of additional response patches would increase the RT to select the correct response patch, and that the magnitude of this effect might depend on the ink color. However, it was unclear whether the pattern of RTs used to estimate perceptual transitions between focal colors would be independent of the stimulus and response sets. For example, the cognitive color space in which alternative representations of color facilitate or interfere may be dynamic, reconfiguring itself for each task according to the context.

Each experimental session consisted of three groups of trials: congruent trials (in which color words were presented in the appropriate focal color); neutral trials (in which color words were presented in black); and mixed trials (in which all combinations of congruent, incongruent, and intermediate colors were presented). By measuring congruent and neutral baselines in each session, we were able to control for general practice and learning effects. In addition, the presence of congruent trials among the incongruent trials is predicted to increase interference (MacLeod, 1991). In each group of trials, each combination was presented four times. Thus, congruent and neutral conditions consisted of 8 trials per session for pure blocks and 16 trials for interleaved blocks, and mixed conditions consisted of 40 trials per session for pure blocks and 80 trials for interleaved blocks. To keep RTs low, observers were warned when their RT exceeded 1200 ms. Incorrect responses were logged and presented again at the end of the session until a complete set of correct responses was obtained. The error rate was displayed on the screen at the end of each session, and observers were asked to keep this below 5%. Each session was repeated 10 times so that each stimulus combination was presented 40 times for each observer.

Experiment 2: Reverse Stroop compared with hue scaling

In the second experiment, we used the four most common color words (red, yellow, green, and blue) and measured reverse Stroop interference for pairs that were spectral neighbors, that is, red to yellow, yellow to green, green to blue, and blue to red. In each case, only two response patches were present. In this experiment, we increased the number of intermediate colors from three to five and the number of repetitions within a session from four to five. Sessions now consisted of 10 trials for congruent and neutral conditions and 70 trials for mixed conditions. Each session was repeated 10 times for observers H.E.S., S.K., L.T.S., and M.D. and 6 times for the remaining observers.

In addition to measuring reverse Stroop interference, we asked observers to make a hue-scaling judgment for each of the four focal colors and all intermediate colors. Similar procedures have been widely used by other authors in studies of color appearance (e.g. Boynton & Gordon, 1965; Abramov et al., 1990; De Valois et al., 1997). The target color was displayed as letters on the CRT, and observers were required to rate the percentage red, yellow, green, and blue, with the requirement that the total should sum to 100 percent. The order of presentation was randomized, and the complete set of 24 chromaticities was repeated three times.

Data analysis

RT distributions were typically positively skewed. Values were log-transformed, outliers that were more than three times the interquartile range above the upper quartile or below the lower quartile were discarded, and the mean of the remaining log-transformed values was back-transformed and taken as the RT estimate. The overall pattern of results is not changed if nonparametric measures are used. Less than 1% of the data were removed as outliers. Average error rates for each observer were below 5%, and the pattern of errors is consistent with our interpretation of RTs, with longer RTs associated with higher error rates.

Results

Experiment 1

Fig. 1B shows average data from nine observers, and error bars show ± 1 standard error (SE). The top row shows RTs for correct responses in the reverse Stroop task. Panels on the left show data for the orange-green pair. Colored-plain symbols show data obtained in pure blocks (when only orange and green response patches were presented), and colored-crossed symbols show the longer RTs obtained in interleaved blocks (when orange, green, red, and yellow response patches were presented). Orange symbols show RTs to select the orange response patch (when the word ORANGE was presented), as a function of the color of the word, from 100% orange on the left to 100% green on the right. Green symbols show RTs to respond correctly to the word GREEN, for the same progression of ink colors. Panels on the right show analogous data for the red-yellow pair.

A contextual change, such as the inclusion of additional response patches, is likely to change the shape of the crossover curves measured in a reverse Stroop task. For example, when the words RED or YELLOW are presented in a 50:50 mixture of red and yellow, the RT to respond either RED or YELLOW is likely to be longer if one of the response patches is orange, since this incorrect response is highly compatible with the appearance of the 50:50 mixture. By plotting, for each ink color, the RT to respond RED minus the RT to respond YELLOW, or the RT to respond ORANGE minus the RT to respond GREEN, we can discount simple variation caused by the similarity of the ink color to irrelevant response patches. In addition, plotting the RT differences, rather than raw RTs, corrects for variation in the latencies of visual responses to stimuli of different chromatic and luminance contrasts (e.g. McKeefry et al., 2003; Smithson & Mollon, 2004). But would RT differences provide a measure of the perceptual transition between two focal colors that is generalizable, in that it is independent of the stimulus and response sets?

The middle row of Fig. 1B shows RT differences for each color-pair, $[RT_{ORANGE} - RT_{GREEN}]$ and $[RT_{RED} - RT_{YELLOW}]$ for the pairs presented separately (colored symbols) or interleaved (crossed symbols). Differences were calculated separately for each observer and then averaged. Error bars show ± 1 SE. Symbols are colour coded according to ink color.

The curves provide a measure of how compatible each ink color is with one or other response (i.e. its relative similarity or dissimilarity to the two focal colors). The curves increase monotonically but not uniformly. For the orange-green transition, RT differences are negative on the orange side of the graph and positive on the green side, indicating an advantage for responding ORANGE when the color mixture is close to orange and an advantage for responding GREEN when the color mixture is close to green. The flat portion to the left of the orange-green curve indicates that the first mixture is as much "orange and not green" as the focal color itself. Similar functions are obtained for the red-yellow transition, though here the rate of change decelerates toward yellow.

Curves measured in the blocked and interleaved conditions are similar in shape but appear to be shifted versions of one another. A 2×5 (blocked/interleaved $\times$ ink color) within-subjects analysis of variance (ANOVA) for each color pair confirms no interaction (orange-green: $P = 0.33$; red-yellow: $P = 0.85$), but significant main effects of blocking and of ink color (orange-green: $P = 0.003$, $P < 0.001$; red-yellow: $P = 0.011$, $P < 0.001$).

There may be a difference in the amount of time required to read and process different color words, and a possible response bias caused for example by differences in the saliency of the correct response patch. We can compensate for these differences by shifting the curves vertically according to the RTs measured in the appropriate neutral condition (see Materials and methods). The bottom row of Fig. 1B shows RT differences adjusted in this way, and data obtained in interleaved blocks have been brought into alignment with data obtained in pure blocks.

The similarities between the shifted curves suggest that the reverse Stroop effect can indeed be used to derive a generalized representation of the color space in which the interference and facilitation occur.

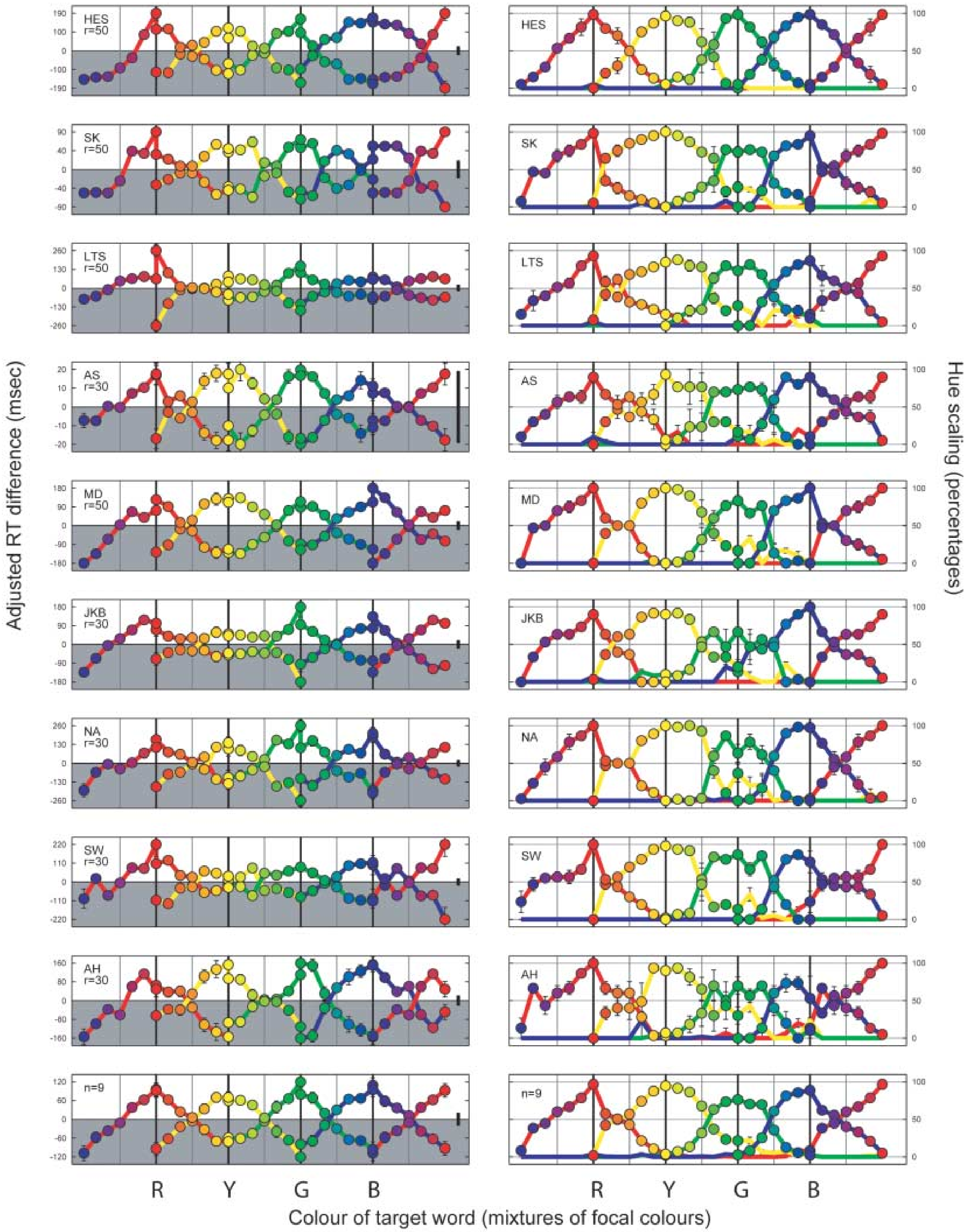
Experiment 2

The left-hand column of Fig. 2 shows RT differences corrected by the relevant neutral RTs (i.e. data analogous to those shown in the bottom row of Fig. 1B) for the color transitions red to yellow, yellow to green, green to blue, and blue to red. The nine observers are shown separately in rows one to nine, and the average across observers is shown in the bottom row. The gray portions of the plots indicate negative RT differences, and the white portions indicate positive RT differences. Each data point is color coded according to the distracting ink color, and the data have been arranged in spectral order. Data for the blue to red transition are repeated at both ends of the plot to indicate the cyclical nature of hue space. Thick black vertical lines indicate focal ink colors (red, yellow, green, and blue). Thin gray vertical lines indicate the midpoints between two focal colors. For each ink color, there are two data points: $[RT_A - RT_B]$ and $[RT_B - RT_A]$, where A and B are a pair of focal colors. The lines through the data points are color coded: the $[RT_A - RT_B]$ curve is color B, since positive values of $[RT_A - RT_B]$ identify the region where ink color is more compatible with color B; whereas the $[RT_A - RT_B]$ curve is color A, since positive values of $[RT_B - RT_A]$ identify the region where ink color is more compatible with color A. Thick black bars to the right of the plots indicate ± 20 ms to show the variation in the magnitude of the reverse Stroop effect for each observer, and error bars show 95% confidence intervals.

As discussed above, RT differences provide a measure of the compatibility of each distracting color with one or other response. The curves therefore map out the regions of color space that are more strongly associated with (i) red (and not blue or yellow), (ii) yellow (and not red or green), (iii) green (and not yellow or blue), and (iv) blue (and not green or red). RT difference curves are generally monotonic functions.

Three important asymmetries should be noted from these plots. First, the reverse Stroop interference for responding to word A presented in color B is not necessarily equal to the interference for responding to word B presented in color A. For example, for observer M.D. (Fig. 2, left column, fifth row), presenting the word BLUE in red causes less interference than presenting RED in blue (i.e. the blue-red crossover curve shows a 180-ms difference for blue ink but only a 90-ms difference for red ink). This suggests that, for this observer, the chromaticities around red are less strongly associated with the word RED than the chromaticities around blue are associated with the word BLUE. Second, a 50:50 mixture of colors A and B does not produce perfectly balanced RTs to respond to the words A and B. For example, for observer H.E.S. (Fig. 2, left column, first row), the crossovers (i.e. the points at which $[RT_A - RT_B]$ and $[RT_B - RT_A]$ are equal, and equal to zero) are closer to red for the blue-red transition and closer to green for the green-blue transition. Third, the responses to word B are not necessarily facilitated to the same relative extent when colors A and B are put in opposition as when colors B and C are put in opposition (where A and C are the spectral neighbors of B). For example, for observer L.T.S. (Fig. 2, left column, third row), the RT difference for RED presented in yellow *vs.* YELLOW presented in red is large (260 ms), compared with the RT difference for RED presented in blue *vs.* BLUE presented in red (35 ms).

We have chosen to represent our stimuli on a color-mixture scale in which the unique hues (red, yellow, green, and blue) are equally spaced. This scale is somewhat arbitrary but has the benefit of not depending on other perceptual data. The asymmetries we observe in our reverse Stroop data suggest that the four unique hues are not equally dissimilar in terms of reverse Stroop interference. In the average data (see Fig. 2, left column, bottom row), the interference for GREEN presented in yellow is greater than the interference for GREEN presented in blue, and the green-blue


HES
r=50
SK
r=50
LTS
r=50
AS
r=30
MD
r=50
JKB
r=30
NA
r=30
SW
r=30
AH
r=30
n=9
Adjusted RT difference (msec)
Hue scaling (percentages)
R Y G B
R Y G B
Colour of target word (mixtures of focal colours)

crossover is closer to green, which further suggests that (in our metric) color space is compressed on the blue side of green compared with the yellow side. Results like these will, we hope, allow us to map the relationship between sensory input and central representations of color.

The right-hand column of Fig. 2 shows data from the hue-scaling experiment. Again, each data point is color coded according to ink color, and data are arranged in spectral order as for the reverse Stroop data. It is important to note that the reverse Stroop and the hue-scaling data were obtained for the same set of color samples, so that the color scales in the two types of plot are entirely comparable. For the hue-scaling data, solid lines through the data points are color coded according to whether they represent the percentage of red, yellow, green, or blue. Thin gray horizontal lines indicate 0%, 50%, and 100%.

The appropriate identification of focal chromaticities from preliminary experiments is confirmed by the hue-scaling data since the functions peak at the locations of the focal colors, indicated by solid vertical lines. There are two interesting features of the data. First, all naive observers chose constant ratios over a range of three to four samples at some point in the range. Second, all naive observers had difficulty around the green point. The green focal color was rarely judged as 100% green, and color mixtures of green and yellow, and of green and blue, varied markedly in saturation and in brightness as well as in hue. These features highlight the subjective nature of the technique and its dependence on experience and strategy. However, there are reliable trends across observers that are borne out in the average data (see Fig. 2, right column, bottom row). For example, the red curve falls steeply toward yellow, and the blue curve falls steeply toward red.

In both the reverse Stroop and hue-scaling paradigms, observers were required to make a response choice between color categories. In the reverse Stroop task, observers were explicitly restricted to only two color categories. In making percentage hue estimates, observers typically also relied on only two categories, although they were not explicitly instructed to do so.

A first glance at the bottom row of Fig. 2 establishes the general similarity between the average reverse Stroop and hue-scaling data. Both the RT differences and the highest hue percentages peak at the focal examples of each color word (red, yellow, green, and blue), and the variation between observers is similar in both functions (see error bars). Furthermore, the RT differences and hue-scaling percentages show a similar dependence on the linear combinations of focal colors. However, a closer inspection reveals intriguing differences. In particular, the crossover points between color categories are displaced relative to one another in the two types of function. For example, the red-yellow crossover point is located at the 50:50 mixture in the reverse Stoop data but is shifted toward the red focal color in the hue-scaling data. Similarly, the blue-red crossover point is located near the 50:50 mixture in the reverse Stoop data but is shifted toward the blue focal color in the hue-scaling data.

Discussion

With a coarse sampling of color space (five points corresponding to yellow, green, orange, blue, and purple), Klopfer (1996) has shown that the amount of interference in a Stroop task is related to the similarity between ink color and target word. However, determination of the fine chromatic tuning of the representations underlying the Stroop effect has resisted study, presumably because color cannot easily be manipulated in a Stroop task. One approach has been to pre-train observers to make an association between a particular symbol and a target color name, before later requiring them to respond with the appropriate color name in response to target symbols presented in varying distracting colors (Buckelmuller et al., 2002; Kiper et al., 2002). The effects that are found are comparable to ours, and there is, in addition, a good correspondence between the magnitude of Stroop interference and hue-scaling data (Cardinal et al., 2003). The effects, however, are highly variable, perhaps owing to variation in the success of the pre-training stage. Interestingly, these studies indicate that systematically tuned interference can occur with newly learned associations between symbols and chromaticities.

Historically, reverse Stroop effects have been more difficult to measure than Stroop effects, and they generally require an experimental manipulation that disadvantages the lexical information: Stroop (1935) found reverse Stroop effects after extensive practice on the Stroop task; Melara and Mounts (1993) reduced text size; Gumenik and Glass (1970) and Dyer and Severance (1972) used a masking stimulus to impair text legibility; de Weert et al. (1999) used text that was isoluminant with the background; and Sugg and McDonald (1994) manipulated stimulus onset asynchrony (SOA) between presentation of the color and the word. However, the task introduced by Durgin (2000), which we used in this study, requires little training, produces reliable long-lived effects that are resilient to practice, and allows independent manipulation of the distracting ink color.

Fig. 2. Data for Experiment 2. Left-hand column: reverse Stroop data. RT differences are corrected by the relevant neutral RTs (i.e. analogous to Fig. 1B, bottom row) for our nine observers (rows 1 to 9). The bottom row shows the mean across observers. Negative RT differences plot below the midline (gray regions), and positive RT differences plot above the midline. Each data point is color coded according to the distracting ink color, and data have been arranged in spectral order (red-yellow-green-blue-red). Data for the blue to red transition are repeated at the ends of the plot to indicate the cyclic nature of hue space. Thick black vertical lines indicate focal ink colors (red, yellow, green, and blue), and thin gray vertical lines indicate the midpoints between two focal colors. For each ink color, there are two data points: $[RT_A - RT_B]$ and $[RT_B - RT_A]$, where A and B are the pair of focal colors. The lines through the data points are color coded: $[RT_A - RT_B]$ in color B, and $[RT_A - RT_B]$ in color A. A different vertical scale is used for each observer, and thick black bars to the right of the plots indicate ± 20 ms. Error bars for individual observers show 95% confidence intervals, and the number of repetitions per point (r) is indicated. Error bars for the average data show ± 1 SE. Right-hand column: hue scaling data. Individual and mean data for the same nine observers. Colored curves indicate the proportion of red, yellow, green, and blue for each of the 24 color samples used in Experiment 2. As in the left-hand column, each data point is color coded according to the sample color, and data have been arranged in spectral order (red-yellow-green-blue-red). Data for the blue to red transition are repeated at the ends of the plot and vertical lines indicate focal colors (black) and midpoints between focal colors (gray). Gray horizontal lines indicate 0%, 50%, and 100%. Each data point, for each observer, is the mean of three ratings, and error bars show ± 1 SE.

We find that the magnitude of reverse Stroop interference does depend systematically on fine gradations of color difference between the ink color and the correct response indicated by the color word. In Experiment 1, we show that the RT to select the correct response patch is influenced by the response patches present, but that the difference in RT to respond to one category or another is a robust measure of the rate of transition between the two categories. Thus, reverse Stroop interference can be used to map the relationship between sensory input and color representations at some central, cortical level. In Experiment 2, we show that the color representations underlying reverse Stroop interference are qualitatively similar to those revealed by hue scaling. The reverse Stroop experiments, however, provide more objective data, which are more amenable to experimental manipulation.

RT-difference curves reveal gradual transitions between spectrally neighboring unique hues, which suggests that, at the locus of reverse Stroop interference, color representation is distributed rather than being strongly divided into congruent *vs.* incongruent categories. However, the data for some observers do show steplike transitions between some color samples, which may reflect intermediate color categories. Further measurements (e.g. with finer sampling of color names) would be required to test the resolution of the color representation.

The marked similarities between the reverse Stroop and hue-scaling data suggest that the reverse Stroop paradigm can be used as a means of investigating color categories. Yet, the subtle differences between the two techniques suggest that the color representations involved in reverse Stroop interference may depend on different retinocortical stages than the color categories revealed by hue-scaling experiments. The neural processing of color (for review, see Gegenfurtner & Kiper, 2003) occurs in several stages each with a characteristic organization, from color opponency in retina and lateral geniculate nucleus (LGN) (e.g. Derrington et al., 1984), to narrowly tuned, higher order, cortical color mechanisms (for review, see Krauskopf, 1999) and cells in inferior-temporal cortex (IT) whose selectivities have been described as reflecting those of the basic color categories (Komatsu et al., 1992). Translation models of Stroop and reverse Stroop interference (Virzi & Egeth, 1985; Durgin, 2003) assume that the internal representation that is intermediate between stimulus and response may require translation into the form that is required to solve the cognitive task. In the reverse Stroop task, Durgin (2003) speculates that the initial lexical code must be translated to a sensory code before performing a visual search for the correct response patch. How this internal representation of color (lexical, sensory, or otherwise) is encoded in human cortex remains unknown. In subsequent experiments, we will further quantify the perceptual mapping of the color space that underlies reverse Stroop interference and facilitation.

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