# Effective colors for information design: A color-coding study of China's high-speed railway map

## Abstract

This study evaluated the effect of China's high-speed railway map's color system based on color design principles in information design, various design limitations of the color system were identified and analyzed. A new color system was re-coded and received satisfying effect in the usability test and enhanced the legibility of the map. The research helps to explore the effect of colors in map design and provides valuable color-coding guidance, which may be applied in map design and other information design materials. The color evaluation, re-coding and usability test methods may bring practical insights for information design and color design researchers.

**Keywords:** Information design, color, legibility, map design

## 1. Introduction

Colors make messages clear and emphasize the key information in the reading materials (Horton, 1994). Colors also help to attract and direct the user's attention in the reading process, and even guide users to the places the designer hopes to highlight (Holtzschue, 2017). According to Horton (1994), "color coding" is one of the most effective techniques in making a target more outstanding. Colors always assist users in effectively locating target information in a disordered or complicated display environment (Brychtova & Coltekin, 2016).

The use of color is an important topic in cartographic design, designers must choose the colors carefully, as the users may read a map in a time-critical situation (Wu et al., 2020). In transit map design, color is one of the most effective tools to discriminate between different transit lines (Burch, 2018). Netzel (2017) and Burch's (2018) eye-tracking tests demonstrated how colors facilitate visual interpretation of transit maps and how deficiencies in color-design can lead to errors in searching for information. Most current studies focused on comparisons of transit-map color designs based on readability tests, but lacked actual color-coding practices (Wu et al., 2020).

A tough question to answer is what is the best color-design choice for a transit map? Many researchers have investigated this topic. Healey (2007) claims that selecting colors with larger color distance is suitable for presenting nominal data, such as transit lines on a railway map, or political affiliations on a world map. Ware (2004) recommends the six opponent-channel colors (red, green, yellow, blue, black, and white) followed by six other distinct colors (pink, cyan, gray, orange, brown, and purple) for this purpose. The value and saturation variations enable more colors to be selected than eight distinguishable colors found in the rainbow system. However, most studies focused on transit map color design were comparison studies rather than color-coding practices (Wu et al., 2021). This study will fill this gap by redesigning a new color system and testing its effectiveness.

The high-speed railway was the most popular transportation choice among international travelers (more than 63 million) who visited China in 2019 (Ministry of Transport of the People's Republic of China, 2020). Its high demand and use show the importance of a well-designed transit map of China's high-speed railway system, the English version network was updated in 2017 (Figure 1), then widely used in most popular railway stations. The Ministry of Transport (PRC) acknowledges the need to evaluate the design quality of China's current high-speed railway map, and improve its effectiveness by information designers (Wang et. al 2021).

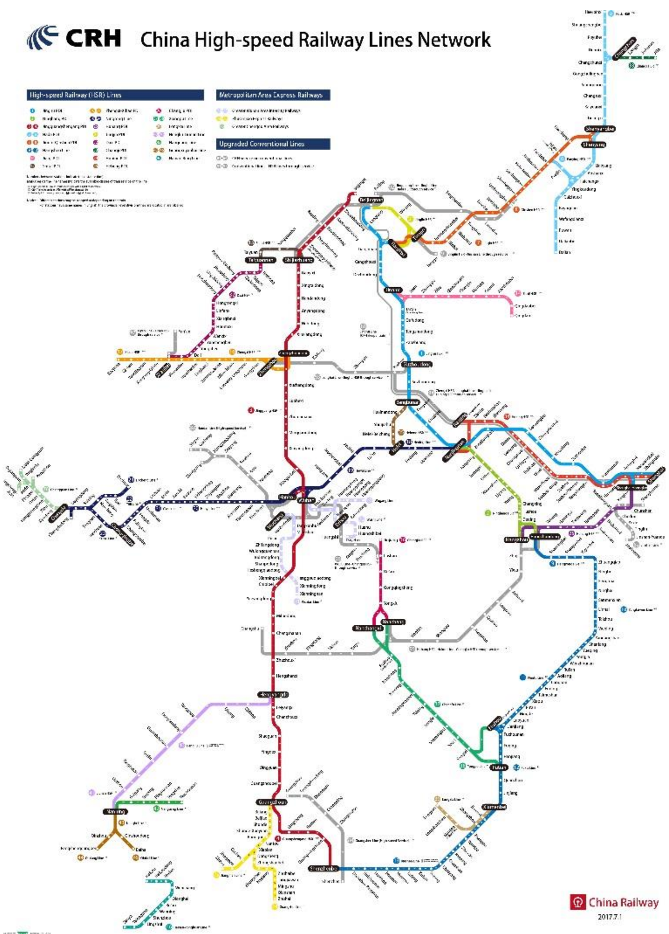



***Figure 2:*** *China's High-speed Railway map*

An earlier study (Wang et al., 2021) suggested one limitation of the design quality of the China's high-speed railway map is the non-optimal use of colors. The aim of this study is to investigate thoroughly such limitation and to suggest and revise color design to resolve it. Three research questions are:

1. What are the suitable color-design principles and color theories applicable to map design?
2. Is the current China's high-speed railway map color design apply to map color-coding principles and color harmony theories?
3. What design solutions can be implemented in the map's color design to enhance design quality, specifically users' speed and accuracy when they search for information?

## 2. Color design principles and color theories for map design

A well-designed color system can greatly assist users in finding their target information on a map without referring back to the map legend (Bertin, 1981). A larger distance between colors can enhance readers' response time in reading the map (Holtzschue, 2017), and McGranaghan (1989) found that lighter colors can represent high-data categories to create strong contrast on the map, especially helpful when emphasizing important transit lines in complicated network systems.

Lloyd et al., (2018) found that coloring by **route** (routes colored as separate lines) is the best color plan for users, rather than trunk (the trunk is colored as one line) and shaded (same color but different shade for the routes). See examples in Figure 2.

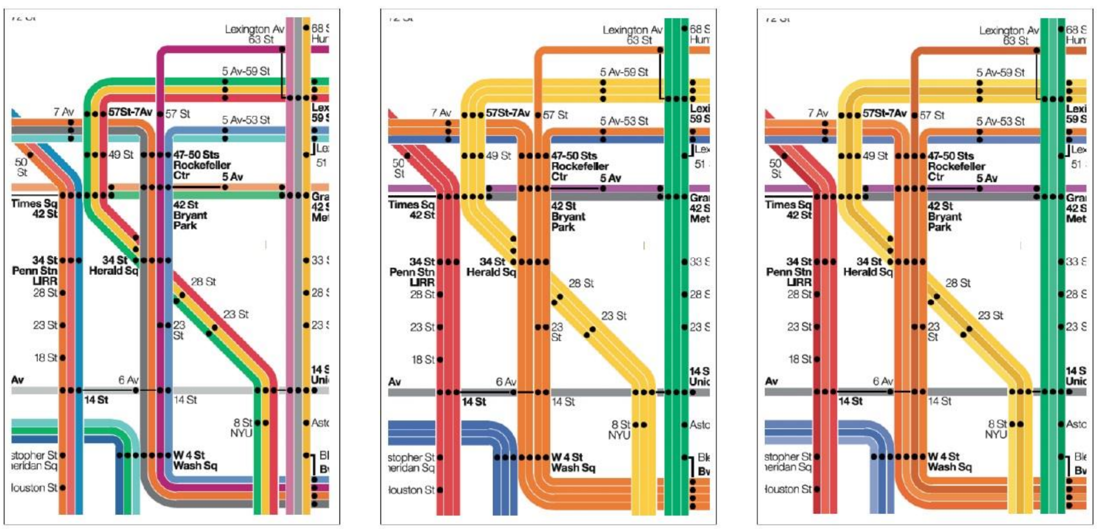



***Figure 2:*** *Examples of lines colored by routes (left), both trunked (middle) and shaded (right) (New York Metro Map, updated in 2009)*

In map design, there are some color-scheme guidelines that can be followed. In Brewer's (1994) research, the author summarized some detailed color-combination plans based on different data needs, such as one-variable data schemes, two-variable data schemes, and duplicate-variable data schemes, etc. But in transit map design, almost all information belongs to **one-variable data**, such as the different names of the lines.

When using colors to display one-variable data on a map, there are four basic color schemes: qualitative, binary, sequential, and diverging (Brewer, 1994). They have different characteristics in hue and brightness, and each of them may apply to different maps with specific needs, such as the qualitative scheme is suitable to transit maps with numerous lines. More details and examples of the four schemes are shown in Table 1.

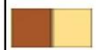
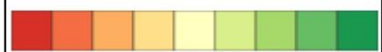
| One-variable data colour schemes | | | |
|---|---|---|---|
| **Data type** | **Hue** | **Brightness** | **Example (RGB colors)** |
| Qualitative | Different hues (not ordered) | Similar in brightness |  |
| Binary | Neutrals, one hue or one hue step | Different brightness steps |  |
| Sequential | Neutrals, one hue or hue transition | Single sequence of brightness steps |  |
| Diverging | Two hues, one hue and neutrals or two hue transitions | Two diverging sequences of brightness steps |  |

***Table 1:*** *Details and examples of qualitative, binary, sequential, and diverging color schemes*

In map design, it is not only necessary to keep strong contrasts among neighboring colors, but it is also important to create **color harmony** to enhance users' visual comfort. A map with a harmonious color system can attract users to explore more information on the map. Research also showed that harmonious colors are also helpful in enhancing the legibility of a map (Goldstein, 1965; Liu & Lin, 2009). Judd and Wyszecki (1975) explained color harmony as two or more colors in neighboring areas that create a pleasing effect.

Many researchers investigated color harmony with different views. There are differences that exist between different color-harmony theories, but some principles are widely recognized, such as monochromatic colors, complementary colors, etc. (Ou, 2016). More details are summarized in Table 2.

| Color harmony categories | Meaning | Example (RGB colors) |
|---|---|---|
| Monochromatic color harmony | The hue of chosen colors is the same or close (Westland et al., 2012). |  |
| Complementary color harmony | Opposite colors located on a hue circle (Itten and Birren, 1997). |  |
| Analogous harmony | Three chosen colors, two of them are either side of the complement of the third in the hue circle (Feisner, 2006). |  |
| Split-complementary harmony | Three chosen colors, two of them are either side of the complement of the third in the hue circle (Feisner, 2006). |  |
| Unequal brightness values | When brightness difference between colors gets smaller, the harmony of the combination gets weaker (Wong, 1986). |  |
| High brightness | The higher the brightness value of colors in a combination, the more color harmony will appear (Granville, 1987). |  |
| Hue preference | In most cases, blue is the hue that is most likely to create harmony and red is the least (Holtzschue, 2017). |  |

***Table 2:*** *Color harmony principles and examples*

## 3. Evaluation of the color system of China's current high-speed railway map

First, the 27 colors presented on the map were divided into six categories according to their hues, their corresponding RGB values, their saturation (S), and their brightness (V) as listed correspondingly in Figure 3.

Research showed that strong contrast between colors can make objects look more distinct on a map (Brychtova & Coltekin, 2016). Colors of the existing map can briefly summarize in six main categories (Figure 2). Although most colors can show different lines clearly, but weaker contrast between lines, such as No. 34 (Huning PDL) and No. 7–8 (Jinqin-Qinshen PDL), No. 9–13 (Hangshen Line) and No. 1 (Jinghu PDL) caused the most errors in information-searching in the test (Wang et al., 2020). This indicates that the weaker color contrast between lines may affect the accuracy of searching for information on a transit map.

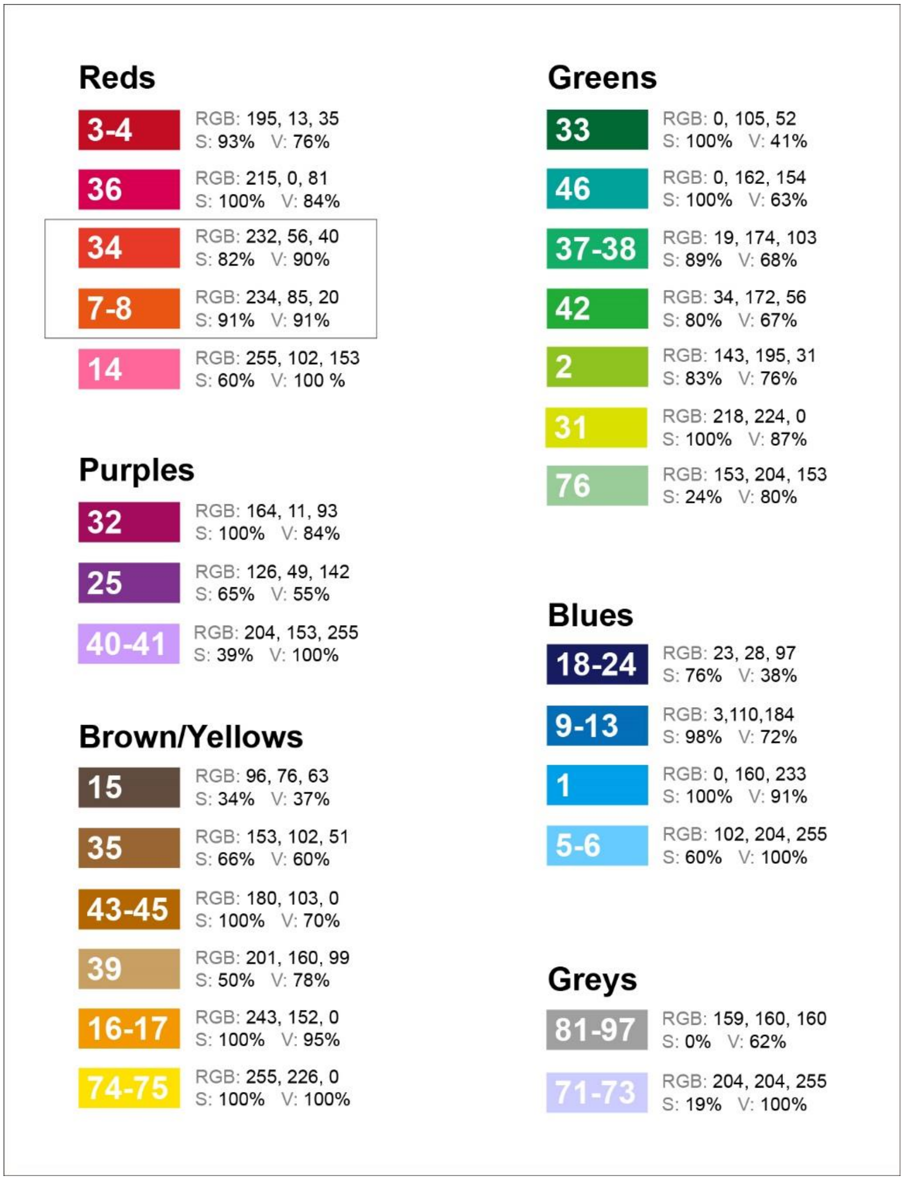



***Figure 3:*** *Six hue categories of colors on China's high-speed railway map (numbers in colored blocks represent railway line numbers)*

## 3.1. Are the colors following map color-design principles?

As mentioned previously in Section 2, there are four main color schemes in map design when one-variable data needs to be presented: qualitative, binary, sequential, and diverging (Brewer, 1994). Currently the different lines' names are the only variable.

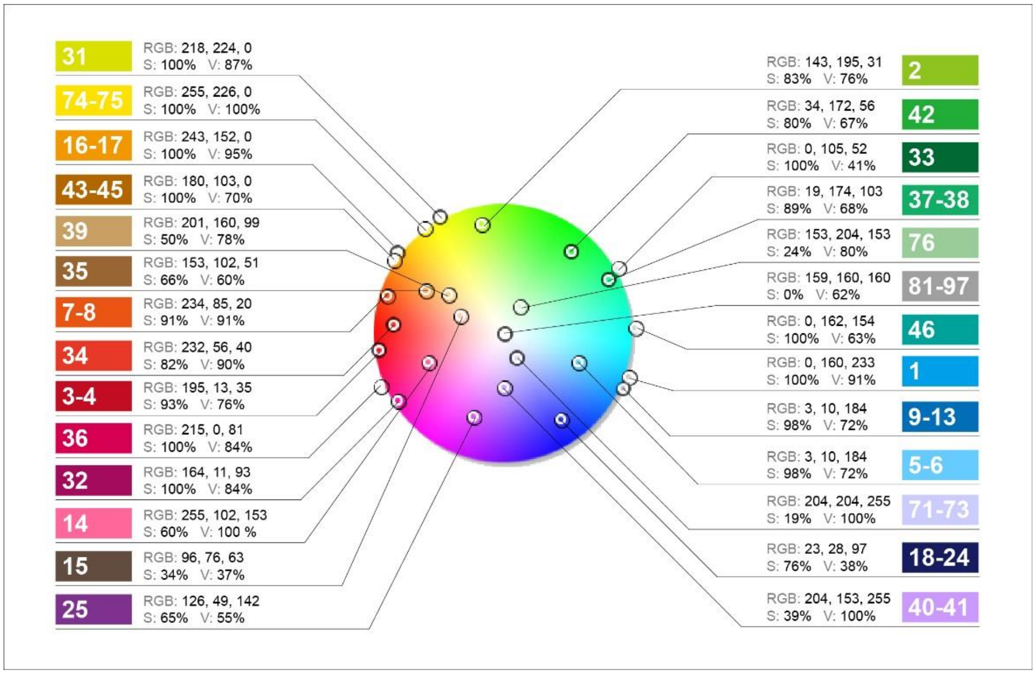



***Figure 4:*** *All 27 colors on the color wheel (information includes RGB value, saturation, and brightness)*

A qualitative color scheme allows differences in hues, but the brightness values of colors need to be the same or similar. According to Figure 3, the brightness values among colors are distinct. They are more likely to belong to the ordinal-relationship color scheme, which is a special category of qualitative color schemes (Brewer et al., 2003). Ordinal-relationship color schemes emphasize different levels of brightness, but they require regularly neighboring hues on the color wheel or complementary color groups. There are many color schemes, such as the Pantone color palette, but at this stage, the RGB color wheel for designers in Adobe Photoshop was selected to show the distances between colors (Figure 3). The white dots represent all 27 colors' corresponding locations on the color wheel. Also in Figure 3, the colors located irregularly on the wheel do not follow the neighboring color selection or complementary color-selection rules. Because of this, the color system is not designed according to the discipline of qualitative color schemes. Some colors are very close to each other, which means they are similar in saturation and brightness, which may cause identification problems in reading.

A binary color scheme is a special case in qualitative color schemes. It contains only two hues to make comparisons between two categories. A diverging color scheme contains two main hues with transitions in brightness values. The current color system contains more than six main categories of hues, which indicates that it is not designed according to binary or diverging color-scheme discipline.

A sequential color scheme follows the rule that colors are arranged according to sequential brightness values with no less than a 10% increase/decrease (McGranaghan, 1989). According to Figure 2, brightness values among all the color categories are not sequentially spaced, which means the color system is not designed according to sequential color-scheme discipline.

Overall, the color system of China's High-speed Railway map is not following any map color-coding principle, it can be considered as a combination of randomly chosen colors.

### 3.2. Are the colors harmonious?

According to Figure 4, the saturation (*M*=0.71, *SD*=0.32) and brightness (*M*=0.75, *SD*=0.19) values are different between all 27 colors. Among all six categories of hues, none have the same or similar saturation, nor do they follow unequal brightness color-harmony rule that brightness and saturation of colors are in descending order (Westland et al., 2012).

Are the colors following complementary color-harmony rules? Taking the most common red-green, orange-blue, and yellow-purple complementary pairs as examples to see more details on the color wheel, Figure 4 shows five colors in the red category and their corresponding complementary colors (colored dots) on the color wheel. All the complementary color dots are located in green-blue hue areas. Meanwhile, seven green colors are displayed on the color wheel, but none of them overlapped with the red colors' complementary color dots. Most of them are actually far away from their complementary colors. This indicates that red colors on the map are not complementarily or analogous harmonious with green colors. Similar results were also found in yellow-purple and orange-blue pairs. Orange and yellow colors on the map are not complementarily harmonious with blue and purple colors (Figure 4).

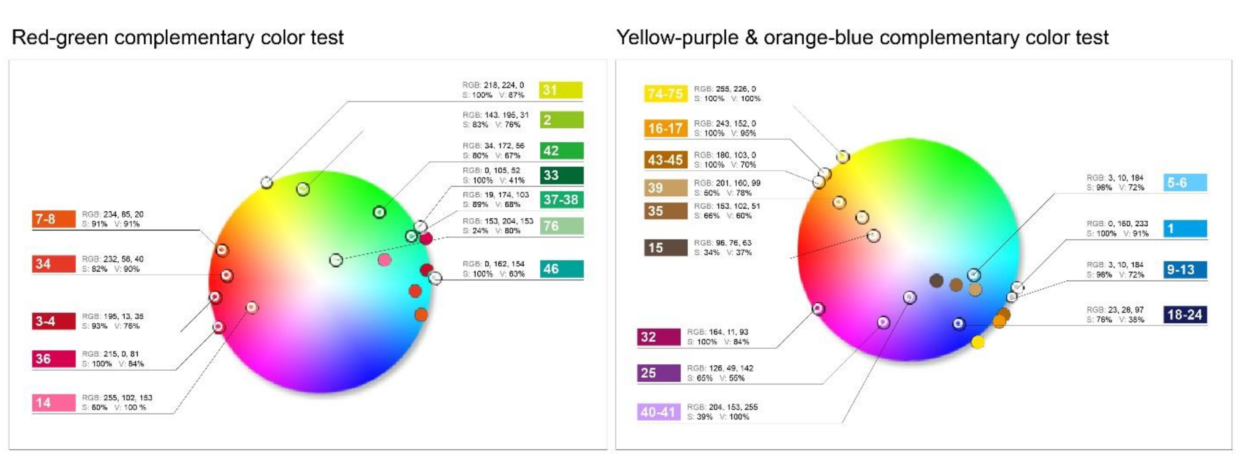



***Figure 5:*** *Colors in the red category and their corresponding complementary colors compare with colors in the green category (left), along with yellow-purple and orange-blue complementary pairs (right)*

Overall, the color system of China's high-speed railway map is not based on the four main color-design principles, nor followed the color-harmony design principles. This could be the reason why the current color system showed less than satisfactory results when read (Wang et al., 2021).

## 4. Reconstruction of the color system in China's high-speed railway map

According to the evaluation results, the current 27 colors belong to six main groups in hue: red, orange/yellow, green/indigo, blue, purple, and gray, a typical rainbow color map. Many researchers pointed out the potential problems of the rainbow color system: the lack of perceptual order could make users feel confused and the random variation in values also obscures the data (Borland & Taylor, 2007).

Borland and Taylor(2007) also found that many users believed there was a potential order to information on cards following a rainbow color order. The rainbow color system is a common default option in many visualization software and applications, such as Visme Map Generator and Infogram. It may be due to users' inertia, and it is very common to see in modern infographic designs. In addition, most maps using rainbow colors separate into bands of almost constant hue with sharp transitions between hues. In this case, users may perceive the sharp transitions in color as sharp transitions in corresponding data.

Due to the reason that the single or paired colors will not be sufficient to differentiate the distinct lines, a color scheme with more color options, such as a qualitative scheme, will be used. Moreover, the sequential scheme provides strong contrast options in every single hue, which is helpful when selecting more neighboring colors. There are 25 colors needed in the new color system: 23 colors represent ordinary railway lines, and 2 colors represent special services (Metropolitan and Upgraded lines).

In the first stage, ColorBrewer, an effective color-selection tool for map designers is used. All color schemes are described using Munsell’s hue, value, and chroma specifications, as well as Munsell’s color-harmony principle (Harrower & Brewer, 2003). Many transit map and geographic-map design examples are based on this color selecting tool (Burch, 2018), such as the newly designed urban railway map in New York (2015), the Danish updated railway network map (2016), and the updated underground map in Berlin (2017). These new design examples achieved better legibility and evaluation in tests and proved the color system is effective. In addition, it has been accepted and recommended by the Cartography and Geographic Information Society in the US since 2005. It is a very welcome and renowned color-selecting tool among cartographic designers, and it has been used in many color-system research and improvement projects (Borland & Taylor, 2005; Brychtova & Coltekin, 2015; Lloyd et al., 2018; Roberts, 2012).

There are eight colors selected by ColorBrewer in our **qualitative scheme**. They are red, blue, green, cyan, orange, yellow, brown, and pink (Figure 6), which follows Ware's (2004) color-selection advice for representing nominal data.

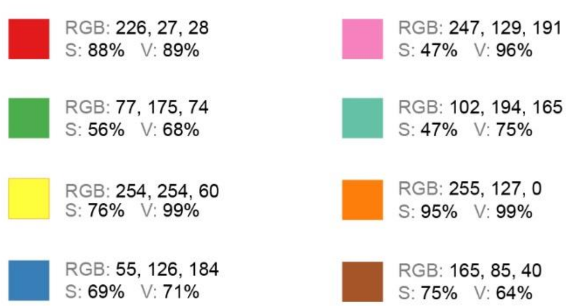



***Figure 6:*** *Colors selected by ColorBrewer*

In Fang et al.'s (2017) research, the color system of the London Underground was improved by adjusting the hue, saturation, and value. The authors adjusted the colors following the method of H: ±5%, and S, L: ±10%. The differentiation of colors among lines were enlarged, which improved legibility in the test. Although research shows that a 10% increase/decrease in lightness is sufficient to show color differences on maps (Fang et al., 2017; McGranaghan, 1989), people with impaired color vision may see less contrast than normal color-vision users. Based on this, another method of H: ±5%, S±15%, and L: ±20% of each selected color to select another two neighboring colors was devised. Details are shown in Figure 7.


***Figure 7:*** *25 Revised colors*

A total of 16 more colors were selected based on this method. Some values increased less than 20% because they already reached 100%, in line with Ou's (2016) conclusion that brighter colors are more likely to create color harmony. In addition, it fulfils the requirement of strong contrasts between transit line colors (Brychtova & Coltekin, 2015; Fang et al., 2017; McGranaghan, 1989).

Because blue hues are more likely to create harmony (Holtzschue 2017; Ou, 2016), and there is an extremely low rate of deficiency to blue among the color-deficient population (Pugliesi & Decanini, 2012), a lighter blue color is selected to represent the three Metropolitan Area Express Railway lines. This bright color is also helpful to show the special service outstanding on the map for color- deficient users.

Compared to the locations of the existing map colors, the colors are more systematically chosen for the revised color set (Figure 8). The revised colors are less saturated and brighter than the existing map colors, more complementary colors are used, which is more likely to create color harmony (McGranaghan, 1989). The revised colors also break the rainbow color order to avoid potential misunderstandings..

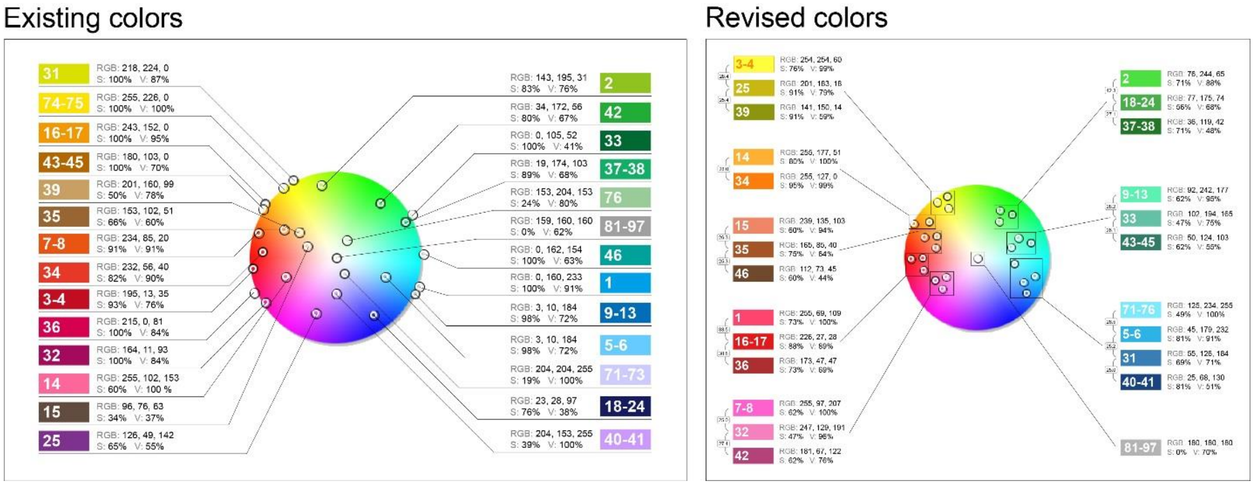



***Figure 8:*** *Existing colors (left) and Revised colors (right) on the color wheel*

In addition, the revised color system uses a blue color to represent all three lines (orange blocks) in the Metropolitan Area Express Railways (blue block), rather than the current three different colors, which avoids potential reading difficulties for color-deficient users (Figure 9). Colors of multiple lines on the existing map (black block) look almost the same (similar blue hues) to red-green color-deficient users (Figure 9), as purple looks very similar to blue for the group (Hess, 2000). In the revised map, such a confused color layout for color-deficient users is avoided.

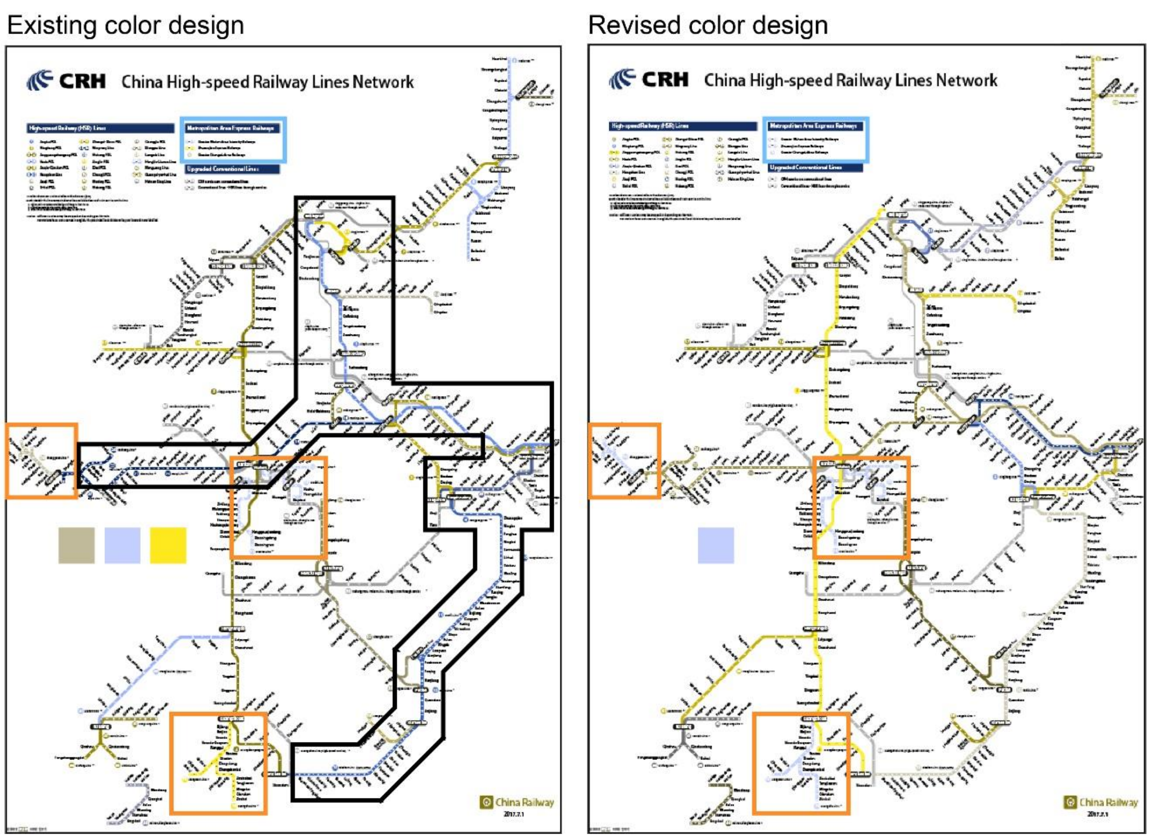



***Figure 9:*** *Red-deficient user's view of both existing map and newly color-coded map*

Overall, the newly designed color system is a **combination of a qualitative scheme and a sequential scheme**. It provides distinct hues and strong contrast transitions among each hue category. The colors are selected based on color-harmony theory and considerations for color-deficient users.

## 5. Usability test

In order to investigate the effects of the newly designed color system and make comparisons of reading speed and information-searching accuracy between the existing map and the revised map (Figure 10), a usability test was conducted among 40 participants. In this test, the layout of both maps is the same, and the two different color systems are the only variants.

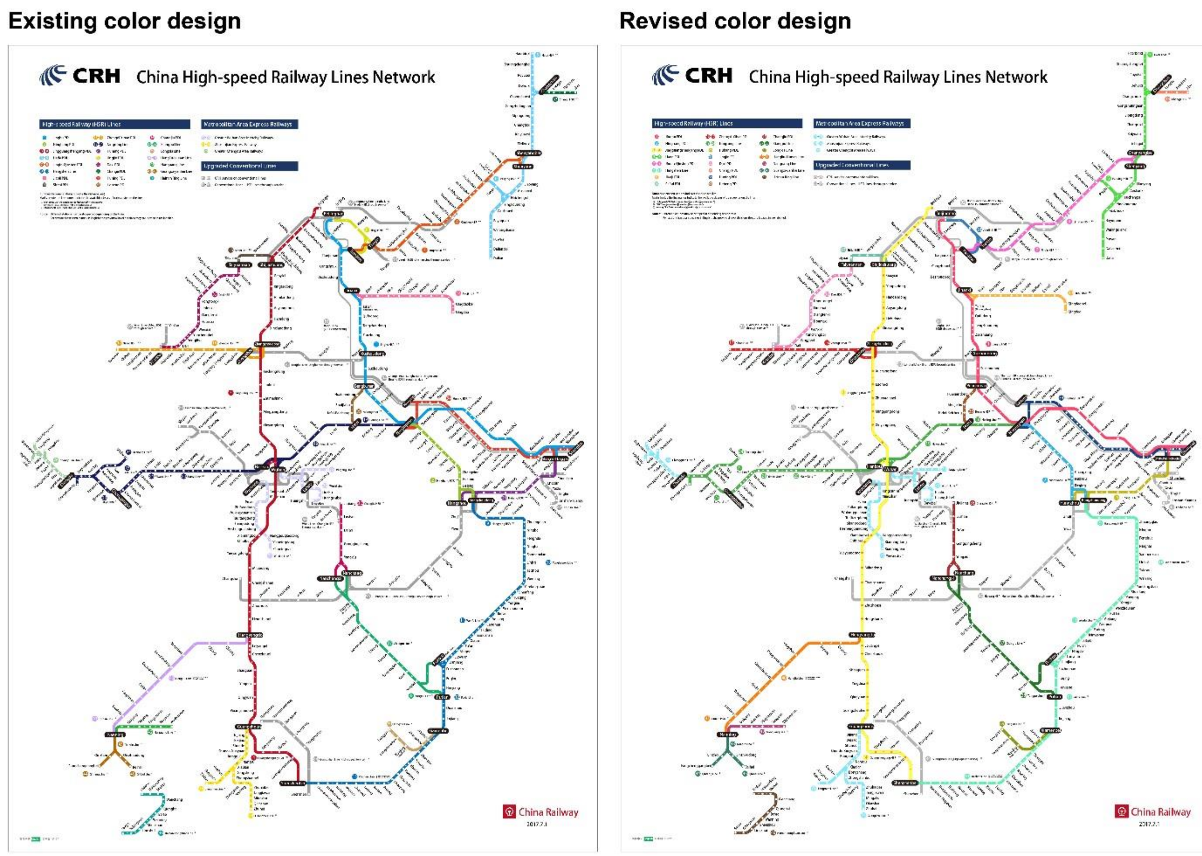



***Figure 10:*** *The existing color design (left) and the revised color design (right) of China's high-speed railway map*

### 5.1. Participants

Forty participants from different educational backgrounds and nations were recruited for this test. They were asked several questions to confirm they were non-Chinese citizens and had no knowledge of Chinese geography, which helped to enhance the objectivity of the results (Wang et. al, 2021). Participants were mainly from the UK, the US, Australia, Canada, India, and Japan. Most of them were from the UK (28, 70.0%).

The numbers of male and female participants were kept the same (20 male and 20 female). The average age of the participants was 25.4, because tourists between 20 to 30 years old made up the largest population (34.4%) of people who visited China in 2019 (Wang et. al, 2021).

In addition, every participant took an Ishihara test (Ishihara, 2018) before the usability test, they were all deemed to have normal color vision.

## 5.2. Test environment, procedure, and materials

The test was conducted in a dark room. Participants needed to complete a total of nine information-searching and route-planning tasks on a computer with a screen resolution of 1920 x 1280 pixels. This screen setting is the same as the screens used in China's railway stations to display maps and relevant travel information. Participants sat in front of the screen at about an 80 cm distance and used a mouse to point out target information. Participants' respond time and information-searching accuracy for each task were recorded.

To increase the validity and reliability of the findings, other analysis methods, such as SPSS calculation, were used. In order to make sure that different groups of data were normally distributed, detailed data-distribution analysis, including histogram, was conducted. In order to make clear comparisons between variables, a paired sample t-test was used.

## 5.3. Test settings

To evaluate the redesigned color system and compare the effects of the existing system to the new one, there was a total of nine information-searching (Type A) and route-planning tasks (Type B) in the test. Two different missions with the same difficulty level were set for the existing and revised maps in each task.

Table 3 shows details of the task settings. Task A1 and Task A2 are transit-line identification tasks, both tasks aim to find out how different color systems affect people's information-searching speed and accuracy. Task A2 aimed to find out if both variates changed after longer time usage of the maps. Task B1 to Task B7 were seven trip-planning tasks. The difficulty of the tasks increased by containing more destinations and interchanges. This aimed to find out the how the different color systems affected users' trip-planning speed and accuracy. Comparison of both variates can evaluate the design quality of both color systems. Participants needed to point to every interchange point and line correctly. Mistakes, such as transferring at the wrong place or planning an impossible route, lost them points.

| Tasks | Instructions | Required targets | Difficulties |
|---|---|---|---|
| A1 | Find 4 transit lines based on colored instructions in the map legend | 8 | N/A |
| B1 | Plan a trip that includes 2 destinations and 1 interchange | 4 | Easy |
| B2 | Plan a trip that includes 2 destinations and 2 interchanges | 6 | ↓ |
| B3 | Plan a trip that includes 2 destinations and 3 interchanges | 8 | |
| B4 | Plan a trip that includes 3 destinations and 5 interchanges | 13 | Medium |
| B5 | Plan a trip that includes 4 destinations and 7 interchanges | 18 | ↓ |
| B6 | Plan a trip that includes 5 destinations and 12 interchanges | 29 | |
| B7 | Plan a trip that includes 7 destinations and 18 interchanges | 43 | Difficult |
| A2 | Find 4 transit lines based on colored instructions in the map legend | 8 | N/A |

***Table 3:*** *Nine tasks in the test*

Taking Task B4, for example (Figure 11), participants needed to plan a trip that included three destinations and five interchanges on each map; the order of both maps is random in each task. Destination locations were marked on the maps, as a station-finding task has a significant chance factor. The time or accuracy of station-finding tasks is not sufficiently objective to support a specific conclusion (Wu et al., 2021).

The % accuracy will be presented by counting the number of correct responses out of the total number of required targets for each task, and there was no time limitation on any task.

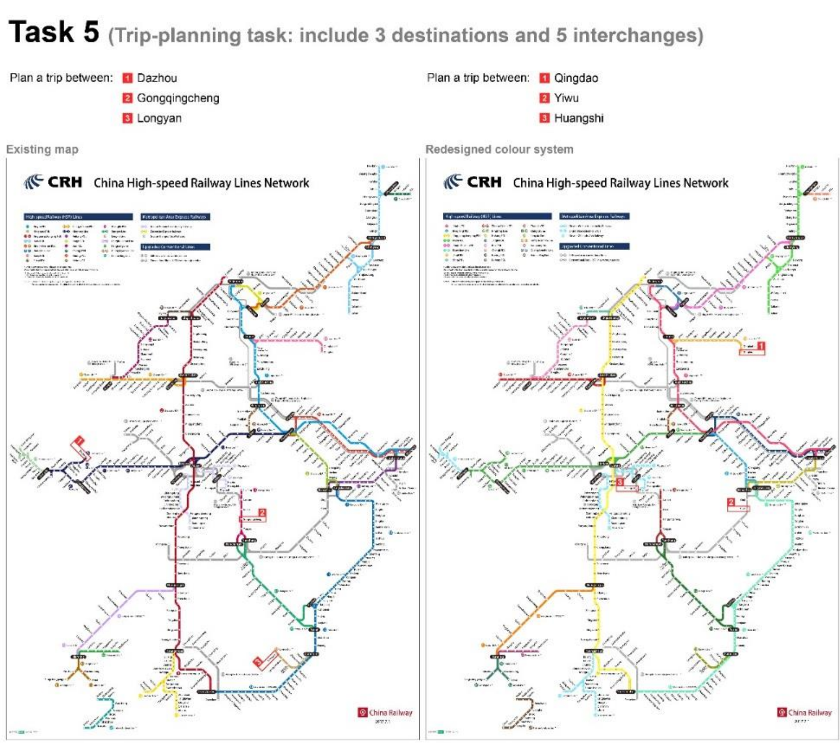



***Figure 11:*** *Task B4, trip-planning missions on both maps*

## 6. Results and analysis

### 6.1. Comparison of reading speeds between existing and new color system

Figure 12 shows the comparison of time consumption between the existing map (blue box) and redesigned color-coded map (green box) in each task; the mean value of each column is emphasized. Overall, participants spent less time in all tasks when using the revised map rather than the existing map.

Both Task A1 and Task A2 were transit-line identification tasks. In both tasks, participants spent less time when using the revised map (*M*=120s in Task A1, *M*=102s in Task A2) than the existing map (*M*=165s in Task A1, *M*=135 in Task A2). Though the difficulty level of both tasks was the same, participants finished Task A2 slightly quicker than Task A1 after going through the previous eight tasks, and the revised map always showed a faster reading speed than the existing map in both tasks.

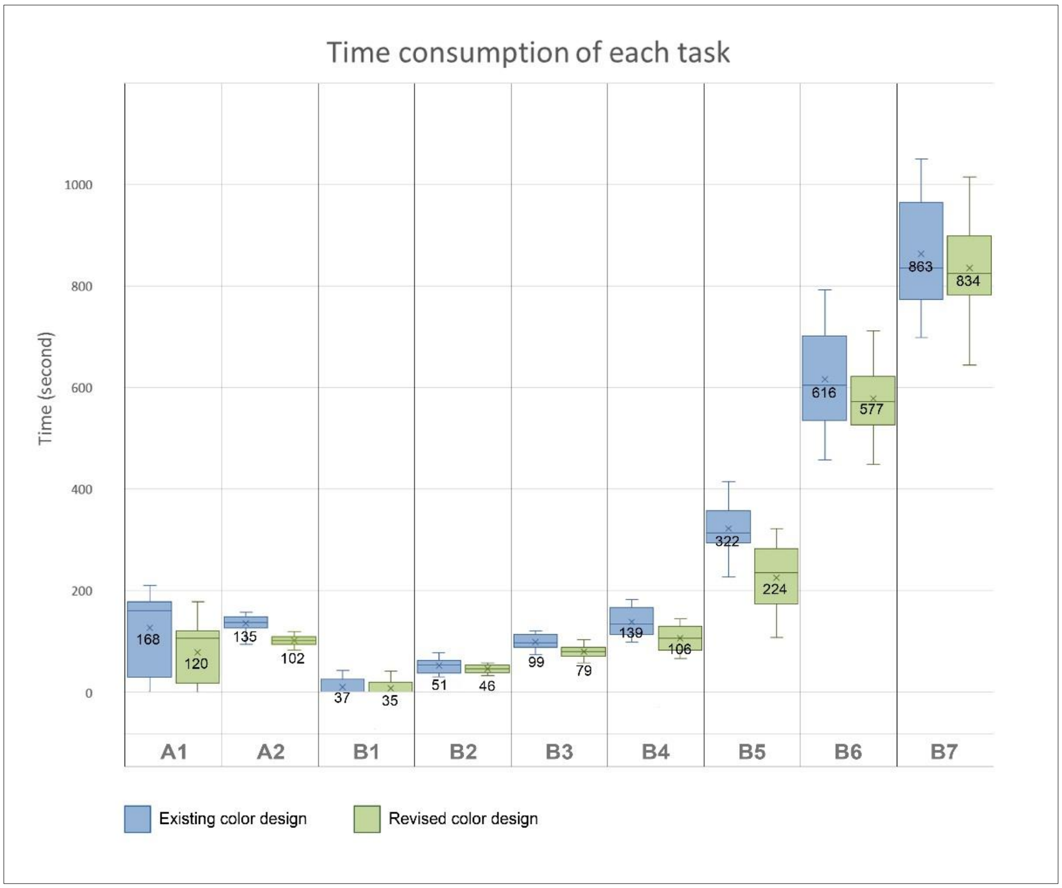



***Figure 12:*** *Time consumption of each task*

Tasks B1 through B7 were route-planning tasks. The difficulty level of the tasks increased from a trip including two destinations and one interchange to a trip including seven destinations and more than fifteen interchanges. Overall, the reading speed for the revised map was faster than the existing map.

With the increase in difficulty, participants' time consumption in the tasks consistently increased. In the most difficult trip-planning task (Task B7), the average time used on both maps was beyond 800 seconds, the longest among all tasks. When comparing participants' time consumption on both maps, the average time participants spent on the revised map in Task B1 ($M^{nB1}$=35s) was only two seconds faster than the existing map ($M^{eB1}$=37s). Then, the differences between both values gradually increased in line with the increasing difficulty from Task B2 ($M^{nB2}$=46s, $M^{eB2}$=51s). The largest significant gap ($p < .05$) was reached in both values in Task B5 ($M^{nB5}$=224s, $M^{e\ B5}$=322s), when the participants were an average of 98 seconds faster using the revised map than the existing map. Further interesting results occurred after Task B5: The gaps between both maps' time consumption consistently decreased in Task B6 ($M^{nB6}$=577s, $M^{eB6}$=616s) and Task B7 ($M^{nB7}$=834s, $M^{eB7}$=863s). Especially in Task B7, the time-consumption difference between both maps is not significant at all ($p > .05$). For the most difficult route-planning task in the test, participants were an average of 29 seconds faster on the revised map than the existing map.

### 6.2. Comparison of information-searching accuracies between existing and new color systems

Figure 13 shows the comparison of information-searching accuracies (mean values) between the existing map (blue points) and revised map (green points) in each task; the full score of each task was 10. From Figure 13, it is obvious that participants' information-searching accuracy when using the revised map was higher than the existing map in almost all the tasks. The only exception was Task B1, where all participants planned the route correctly with no mistakes in this simplest trip-planning task.

Both transit-line identifications in Task A1 and Task A2 showed larger differences in information-searching accuracy between both maps ($M^{nA1}$=92.5%, $M^{eA1}$=80%; $M^{nA2}$=96.9%, $M^{eA2}$=90%). The existing map showed a lower accuracy than the revised map in both transit-line identification tasks. The accuracy of both maps in Task A2 was better than in Task A1, which means participants' information-searching accuracy increased after their user experience improved.

In the trip-planning tasks (Task B1 to Task B7), mistakes made by participants consistently increased from Task B2 ($M^{nB2}$=98.8%, $M^{eB2}$=95%) with increased levels of difficulty. The accuracy values reached their lowest in Task B7 ($M^{nB7}$=87.4%, $M^{eB7}$=83%). This indicates that the more difficult the task is, the more mistakes will be made by the users. Overall, the information-searching accuracies of both maps did not show very significant gaps, but the revised map always showed better accuracy than the existing map in trip-planning tasks.

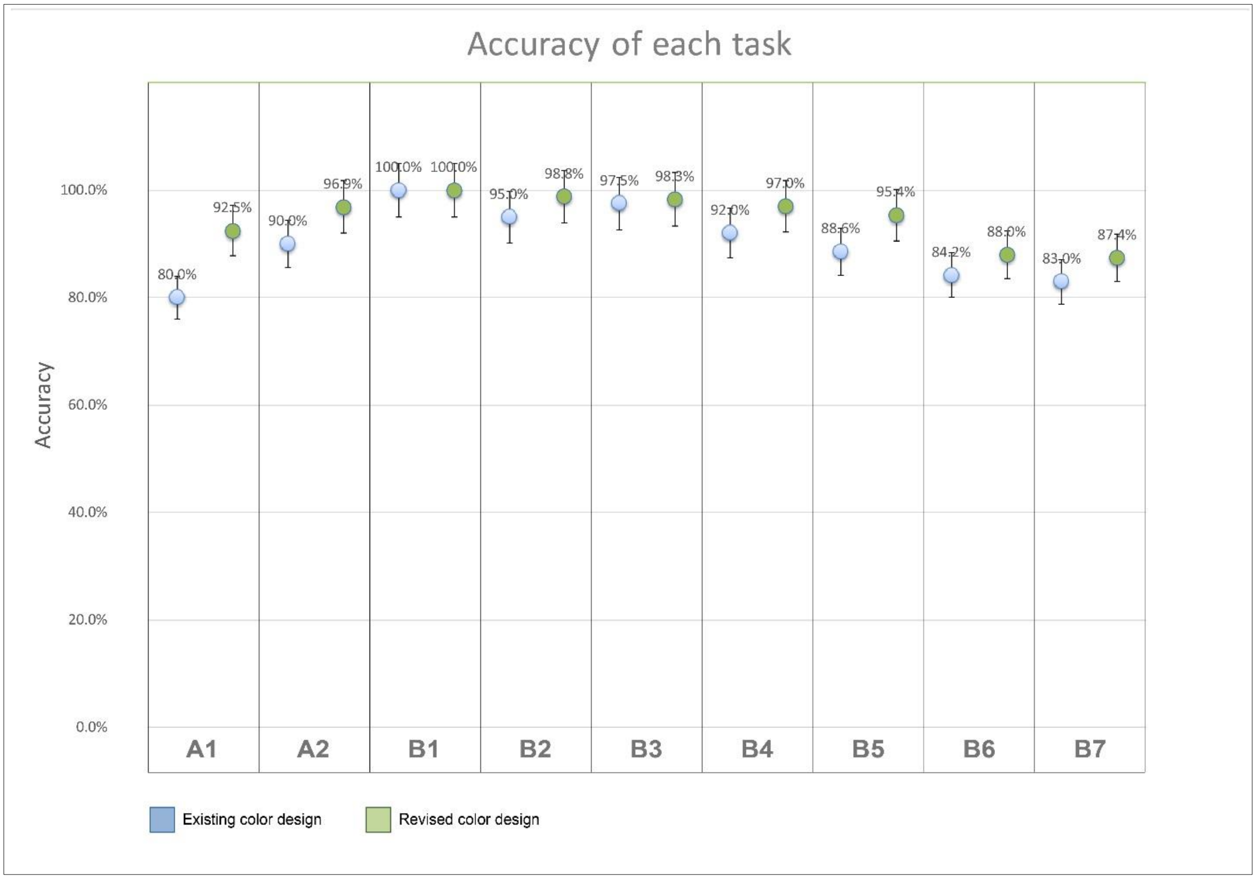



***Figure 13:*** *Information-searching accuracy of each task*

## 7. Discussion

Based on the results of the test, the design quality of the color systems of the existing map and the revised map were effectively compared. Many valuable findings with regard to transit map color-coding and how colors affect a transit map's legibility were identified. Participants also provided various practical insights into the design and evaluation of transit-map color systems.

### 7.1. Effect of colors on a transit map's usability

In the trip-planning tasks (Figure 12), participants finished tasks much quicker when using the revised map than the existing map at the beginning (Task B1). The time-consumption gap between both maps consistently became larger, but as the difficulties of tasks gradually increased, the time consumption gap between both maps became smaller after Task B5. This finding is similar to Netzel et al.'s (2016) eye-tracking test results. They compared users' reading speed and information-searching accuracy between a gray-scale and a colored map of the same transit-line system. The authors found that the colored map showed an advantage in both reading speed and information-searching accuracy at the beginning than the gray-scale map, but as the difficulties of the tasks increased, this gap gradually became smaller. This indicated that the advantage of colors may not exist when the complexity of a task reaches a certain level. Similarly, in this study, although the revised map showed its advantage in reading speed at the beginning, but the differences between both maps became smaller after Task B5 (planning a trip contains four destinations and seven interchanges). This finding indicates that color may not be a key factor in transit-map reading speed in complex route planning (Task B5 in this study). The phenomenon found by Netzel et al., (2016) does not only exist between the color-coded and gray-scale versions but also exists between different color-coded plans.

By examining the trip-planning accuracies (Figure 13) of Task B1 to Task B7, it was clear that the more complex the task was, the more mistakes participants would make on both maps. The revised map showed a slightly better ($p > .05$) information-searching accuracy than the existing map. With the difficulties of the tasks increased; trip-planning accuracy of both maps did not show significant differences. This indicates that colors may have a limited effect on trip-planning accuracy.

The feedback from participants can also explain the effect of colors from a user's perspective. In trip-planning tasks, participants paid more attention to colors at the beginning, as they mentioned that colors were more direct and easier visual elements to target the routes in those simple tasks. With the increases in difficulty, participants started to pay more attention to texts, as they needed to double-check the text information carefully when the complexity of the tasks increased. This showed that the effect of colors on a transit map depends on the difficulty of the task, colors may have weaker effects on a transit map's legibility in complicated route planning tasks. However, this finding may not apply to all users. Individual differences and biases cannot be ignored because some participants may prefer to find information based on text rather than color all the time, or the converse.

## 7.2. Evaluation of the existing and redesigned color systems

Different to the existing map, the new color system was built based on map color-design principles and color-harmony theories, it showed better performance in usability tests.

In both transit-line identification and trip-planning tasks, participants always spent less time using the revised map than the existing map (Figure 12).This may be credited to the stronger color contrast of the new color system that make every transit line more distinct from each other, but it does not mean the existing map failed to represent transit lines clearly.

Considering the information-searching accuracy of both maps, the differences in both transit-line identification tasks (Task A1 and Task A2) were larger than that in trip-planning tasks (Task B1 to Task B7). The major mistake made by participants was being misled by the colors with similar hues to the target lines. For example, in Task A1, there were 16 (40%) participants who mistakenly selected the No. 34 transit line because its red color looks similar to the target line (No. 7-8). Both colors were found to be close in color distance in the previous color-evaluation work (Figure 4). Similar mistakes rarely happened when participants used the revised map, which indicates that the stronger contrasts among colors in the new color system successfully reduced such confusions and led to a better information-searching accuracy, although this advantage was not very significant in trip-planning tasks. But, overall, the new color system enhanced the reading accuracy of China's high-speed railway map.

In addition, participants marked scores of both color systems via Likert scales. The revised colors ($M^n$=4.2, above "Harmonious") are observably more harmonious than the existing map's colors ($M^e$=2.7, under "Neutral"). This may be the benefit of the use of complementary colors, as Itten and Birren (1997) state that complementary pairs or multiple complementary combinations create harmony. Color harmony is relevant to aesthetics. A transit map with harmonious colors can enhance users' interest in map exploration (Goldstein, 1965; Liu & Lin, 2009). The user's satisfaction of the revised map in color harmony may directly lead to its strong attractiveness among users. There were 32 (80%) participants who preferred the revised map, which is four times the number of those who preferred the existing map (8, 20%).

Overall, the results showed that the revised map is superior to the existing map in both reading speed and information-searching accuracy, the new color system shows stronger color harmony and attractiveness as well.

### 7.3. Color coding for transit-map

The results of the usability test showed that the color-recoding work effectively helped to enhance the reading speed and accuracy of the map, as well as its attractiveness., there is some transit map color-design guidance that can be summarized from this study.

The previous evaluation of the existing map's colors showed that the colors were not in line with any map color-design principles or color-harmony theories. Although it could not be considered a mistake in color selection, the existing map showed that randomly selected colors caused weaker contrasts or indistinctive differences between colors (Stigmar, 2010). These problems were identified when testing the color distances and led to inefficient reading in the test. This showed the effectiveness of **color contrast comparison** when evaluating a color system of a transit map.

The combination of a **qualitative scheme** and a **sequential scheme** is considered a suitable color-coding plan for a transit map: The qualitative scheme provides multiple selections of hues to represent a large number of different transit lines, and the sequential scheme provides different lightness and saturation values to enlarge the color distances. The **contrasts** between colors need to be at least 10% to show sufficient **color differences** (Fang et al., 2017; McGranaghan, 1989). This standard has been enlarged in this study. The colors in each hue category kept ±15% in saturation and ±20% in lightness. This method can create stronger contrasts and richer saturations. **Stronger contrasts** can also enhance the transit lines' identification for color- deficient users because they may see weaker contrast than normal color-vision users (MacEachren, 1995; Hess, 2000; Dent et al., 2009).

There are many **complementary colors** used in the new color system, such as red-green pairs and blue-orange pairs. The positions of the revised colors on the color wheel (Figure 12) show their paired complementary relationships. They made transit lines more distinctive and strongly enhanced the color harmony of the revised map, which led to a higher attractiveness for users.

In addition, it is always suggested to have a thorough understanding of the certain area's culture and user preferences in colors, such as, in China, Hongkong and Taiwan, most people believe that the high-saturated red color represents good luck, they may assume that the high-saturated red lines could be more important or special than the others (Tian, 2021), this can cause misunderstandings in reading, that is the reason why less-saturated or darker/lighter reds are used in the new color system to avoid potential mis-judgement from users.

## 8. Conclusions

This study evaluated the design quality of China's existing high-speed railway map's color system. Various problems were found, such as insufficient color contrast, lack of color harmony. A new color system was established based on transit map color-design principles and color-harmony theories, and its effectiveness was tested in a usability test. This study demonstrated a successful theoretical and practical evaluation and redesign process of the color design of a transit map, which filled the gap among studies that focused on comparisons of transit-map color designs but lacked actual color-coding practices (Wu et al., 2021).

The usability test showed that the color-recoding work successfully enhanced the map's reading speed and information-searching accuracy. This proved that the combination of the qualitative and sequential color schemes was a suitable color-coding plan in transit-map design, at least for mid-complex networks. The use of complementary colors was not only helpful to distinguish railway lines but was also useful in creating a stronger color harmony, which led to a high attractiveness. Moreover, this study is a good example of considerations for color-deficient users, design solutions such as enlarging color contrasts and grouping colors in the same service. These practical improvements also successfully solved the color design limitations identified from the earlier study and enhanced the reading efficiency and comfort of the map (Wang et al., 2021), these design advices may be applied to other transit maps with issues in color design, especially for those contained larger amount of lines and different transit services.

This study furtherly investigated how colors affect a transit map's usability. The results showed that colors had a significant effect on the reading speed of a transit map in less complicated tasks, but the advantage of the redesigned color system became weaker after the complexity of tasks reached a certain level. In addition, colors do not have an observable effect on a transit map's information-searching accuracy. However, colors cannot be recognized as the only variate that affect the legibility of the map, other factors such as transit line layout and typography can also significantly influence the design quality and reading comfort of a transit map.

Overall, this study carried out detailed color evaluations, color re-coding, and a color-usability test of a complex transit map, the findings are not only contributing to color design, but also provide useful insights with regard to visual design in cartography. More importantly, the testing and redesign methods, as well as the color design rules practiced in the experiment, could also be applicable to other information design reading materials, especially those that need to display multi-category one variable information, such as instructional guidance for products. In future research, more practical efforts will be made to investigate a better transit map color-coding scheme for color-deficient users, as well as how colors affect reading performance on different terminals, such as smartphones and pads. An eye-tracker may be used to record people's reading behavior and target the potential design limitations more accurately (Wang et al., 2021).

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