External Human-Machine Interfaces: Which of 729 Colors Is Best for Signaling ‘Please (Do not) Cross’?

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***Abstract*—Future automated vehicles may be equipped with external human-machine interfaces (eHMIs) capable of signaling to pedestrians whether or not they can cross the road. There is currently no consensus on the correct colors for eHMIs. Industry and academia have already proposed a variety of eHMI colors, including red and green, as well as colors that are said to be neutral, such as cyan. A confusion that can arise with red and green is whether the color refers to the pedestrian (egocentric perspective) or the automated vehicle (allocentric perspective). We conducted two crowdsourcing experiments (*N* = 2000 each) with images depicting an automated vehicle equipped with an eHMI in the form of a rectangular display on the front bumper. The eHMI had one out of 729 colors from the RGB spectrum. In Experiment 1, participants rated the intuitiveness of a random subset of 100 of these eHMIs for signaling ‘please cross the road’, and in Experiment 2 for ‘please do NOT cross the road’. The results showed that for ‘please cross’, colors close to pure green were considered the most intuitive. For ‘please do NOT cross’, colors close to pure red were rated as the most intuitive, but with high standard deviations among participants. In addition, some participants rated green colors as intuitive for ‘please do NOT cross’. Results were consistent for men and women and for colorblind and non-colorblind persons. It is concluded that eHMIs should be green if the eHMI is intended to signal ‘please cross’, but green and red should be avoided if the eHMI is intended to signal ‘please do NOT cross’. Various neutral colors can be used for that purpose, including cyan, yellow, and purple.**

Keywords—automated driving, crowdsourcing, external human-machine interface, color, intuitiveness

I. Introduction

Automated vehicles (AVs) of the future may be equipped with external Human-Machine Interfaces (eHMIs). An eHMI is a display that can indicate the intentions of the AV to other road users, such as pedestrians [1], [2], cyclists [3], [4], or drivers of manually-driven cars [5].

Bazilinskyy et al. [6] tabulated 22 eHMI concepts that have been proposed by industry. Designs varied widely, ranging from projections on the road surface [1], [2], [7] and text messages behind the windshield [8] or on the front bumper [9], [10], to light strips on the car body [3], [11] and human-like features such as a smile on the front bumper [12] or moving headlights [9], [13]. A survey of the academic literature shows many more concepts, in particular text messages [14]–[18], light strips [19]–[24], icons [14], [15], [25]–[28], and projections [28]–[30].

The large number of available eHMI designs represents a regulatory challenge. As noted in an ISO/TR 23049:2018(E) document on guidelines for external visual communication of automated vehicles: “The format and style of communication signals should be harmonious across OEM’s in order to avoid the use of different messages for different types of vehicles in different countries” [31]. In this paper, we aim to contribute to the challenge of eHMI design by focusing on one eHMI feature: color.

Different colors have been proposed in academic literature and industry, including red, green, cyan, and white (see [6] for an overview). Basic studies on color-word association indicate that red is associated with ‘danger’ and ‘stop’, whereas green is associated with ‘safety’ and ‘go’ [32]–[38]. Previous studies and patents on front brake lights have proposed various colors, including green [39]–[41] and red [42], [43], but also amber [43], [44]. While red and green are usually interpreted correctly in current traffic, these colors can be confusing when used in eHMIs. If red is used as a front brake light, it indicates that the vehicle is slowing down and that the pedestrian can cross the road. If, however, the pedestrian interprets a red front brake light as he would interpret a normal pedestrian traffic light, the pedestrian would be inclined not to cross the road.

In an attempt to solve the red-green conundrum, Bazilinskyy et al. [6] showed 1319 participants images of approaching AVs with red, white, and green eHMIs on the front bumper. Respondents were asked “Would you feel safe to cross in front of the car above?”, with the answer options ‘Yes’, ‘No’, and ‘Not sure’. The results showed than green eHMIs led to more ‘Yes’ responses than white eHMIs, which in turn led to more ‘Yes’ responses than red eHMIs. Essentially, the results of Bazilinskyy et al. suggest that front brake lights should be green, not red. However, free-response items showed that participants were sometimes uncertain, especially if the eHMI concepts did not include an accompanying text message. For example, one respondent remarked “For whom is red?”, a comment that may be related to the egocentric-allocentric confusion mentioned above (see also [45] for an early study of what they called the ‘red-green paradox’). More recent online studies by Bazilinskyy

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et al. [46] and Dey et al. [47] reinforce the conclusion that green is more intuitive than red for indicating to a pedestrian that he/she can safely cross. Furthermore, a red light on a non-yielding AV seems to stimulate participants not to cross the road [46].

A variety of researchers have suggested cyan or turquoise as eHMI colors because these colors are considered to be neutral, have no meaning in current traffic, and are clearly distinguishable from the car's headlights [23], [48], [49]. This recommendation appears to be in line with the vision of the car industry, as a variety of eHMI concepts have a cyan color [1], [7]–[9]. Cyan is further considered to be aesthetically pleasing, which could contribute to greater acceptance of automated vehicles [49]. Cyan can help prevent egocentric-allocentric confusion because a neutral color forces the pedestrian to make a decision based on the traffic context, other features of the eHMI (e.g., a text message), or previously learned meanings of the color. An online survey by Dey et al. [47] concluded that cyan is considered a neutral color for signaling to a pedestrian 'please cross'. However, Dey et al. also noted that some participants regarded cyan as close to green. Bazilinskyy et al. [46] found this green-cyan confusion to be severe in that both cyan and green eHMIs encouraged pedestrians to cross, without significant difference between these two colors. The difference in results between [46] and [47] may be due to the specific shade of cyan (aquamarine in [46], pure cyan in [47]).

Based on the above, it seems necessary to do more research on the topic of eHMI color. Interestingly, some respondents in [47] spontaneously suggested using amber and yellow. As far as we know, there exist no human-subject studies of these eHMI colors. In addition, there is little knowledge about individual differences in eHMI color interpretation. It would be worth investigating not only whether an eHMI color is on average intuitive for participants, but also whether the degree of intuitiveness is consistent between participants. The current study contributes to the debate about the intuitiveness of eHMI colors by letting participants view colors from the full RGB spectrum on the front bumper of an AV, and judge whether the color is intuitive as a representation of the message 'Please cross the road' or 'Please do NOT cross the road'.

II. Method

A. eHMI Concepts

A total of 729 images were generated with an eHMI in the form of a rectangular colored display with a black frame. The colors were chosen from the RGB spectrum in step of 32 for the red, green, and blue values. That is, the first color had RGB values of (0, 0, 0), the second color had the RGB values of (0, 0, 32), and the last color had the RGB values of (255, 255, 255). The eHMIs were positioned on a photo of a test vehicle driving in Delft, The Netherlands (Fig. 1). The photo was made during the preparation of an experiment of Rodríguez Palmeiro et al. [50] and previously used in [6]. We opted for a photo with a driver because future automated driving systems (at least of SAE levels 3 and 4) require that a human can take over control.

B. Experiment 1 ('Please Cross')

The participants subscribed to the online experiment through the crowdsourcing service Appen (https://appen.com). The

Fig. 1. Experiment page with a stimulus, instructions, and a slider to provide the response.

participants became aware of this research through one of many channel websites (e.g., https://www.ysense.com), where our study was available in a list of other projects available for completion. We allowed contributors from all countries to participate. It was not permitted to complete the study more than once with the same worker ID. A payment of USD 0.25 was offered for the completion of the experiment.

First, participants completed a questionnaire regarding their demographic characteristics (age, gender, etc.). Contact information was provided at the top of the questionnaire. The participants were informed that they could contact the researchers to ask questions about the study and that they should be at least 18 years old. Information about anonymity and voluntary participation was provided as well.

Participants then clicked on a link that opened a webpage containing the experiment. The participants were first shown the following information about the task to be performed: "The purpose of this experiment is to determine the intuitiveness of various colors of light presented on the front bumper of an automated vehicle. In the following images, you will see an automated vehicle that stopped in front of you after approaching you. You will view 100 images. Each image will be on a separate page. For each image you will need to answer one question by moving a slider. To advance to the next image, the slider needs to be moved. The window of your browser should be at least 1300px wide and 800px tall."

The participants were required to indicate the intuitiveness of the eHMI for a subset of 100 randomly selected images from the list of 729, by moving a slider below the image. Each image was accompanied by the following statement: "Imagine that you are a pedestrian and the car wants to let you go first. Please rate the following statement: The color on the bumper is intuitive for signaling 'Please cross the road' (0 = completely disagree, 100 = completely agree)." (see Fig. 1). After moving the slider, the button 'Continue' became active, allowing the participant to proceed to the next image. At the top of the page, a bar displayed the progress of the experiment.

At the end of the experiment, the participants were presented with a unique code. Participants were asked to note down this code and return to the questionnaire page. They had to fill in the code on the questionnaire as proof that they had completed the experiment and receive their compensation.

C. *Experiment 2 ('Please Do NOT Cross')*

Experiment 1 measured the intuitiveness of colors for signaling 'please cross the road'. What was missing from Experiment 1 was which color would be considered intuitive for signaling 'please do NOT cross the road'. We conducted a second experiment to investigate this. Experiment 2 was the same as Experiment 1, except that with each photo, we asked, "Imagine that you are a pedestrian and the car wants to go first. Please rate the following statement: The color on the bumper is intuitive for signaling 'please do NOT cross the road' (0 = completely disagree, 100 = completely agree)." Furthermore, the description "automated vehicle that stopped in front of you after approaching you" was changed to "automated vehicle that is approaching you". Finally, as part of the demographic questionnaire, we included a six-item Ishihara test for colorblindness [51]: one item tested for general colorblindness, four items tested for red-green colorblindness, and one item was used as a positive control.

III. Results

A. *Experiment 1 ('Please Cross')*

A total of 2000 people participated between 5 April 2020 and 16 April 2020. The total cost was USD 600. The survey received a satisfaction score of 4.2 on a scale from 1 ('very dissatisfied') to 5 ('very satisfied'). Participants who reported not having read the instructions, who were under the age of 18, or who had not completed the task were removed. If people had completed the study more than once from the same IP address, only the first attempt coming from that IP address was included. In total, 556 participants were removed, leaving 1444 participants.

The retained participants resided in 68 countries, with the most represented countries being Venezuela (N = 518), United States (N = 113), and Russia (N = 80). The sample consisted of 947 males, 496 females, and 1 participant who selected "I prefer not to respond" to the gender question. The mean age of the participants was 36.3 years (SD = 11.2). The participants had used an average of 20.5 min to complete the questionnaire and experiment (median = 16.1 min).

Fig. 2 shows the median intuitiveness ratings sorted in ascending order. The results are consistent with previous studies [46], [47], with green being regarded as intuitive for crossing and red as non-intuitive. An important addition to the literature is that the highest-scoring colors were close to pure green (RGB 0, 255, 0), see Table I. Darker shades of green yielded lower intuitiveness (in the 60–80% range), see Fig. 2. Cyan yielded median intuitiveness scores around 50%, in line with [47]. More specifically, pure cyan (RGB 0, 255, 255), turquoise (RGB 64, 224, 224), and aquamarine (RGB 128, 255, 224) showed median intuitiveness ratings of 55%, 55%, and 57%, respectively. Yellow and brown colors were interpreted below the mid-range (35–50%). Purple, pink, and especially red were regarded as non-intuitive for signaling 'please cross the road'. The lowest-rated colors were the ones close to pure red (RGB 255, 0, 0). Black (RGB 0, 0, 0) was also regarded as non-intuitive (median 7%), whereas white (RGB 255, 255, 255) was regarded as moderately intuitive (median 43%).

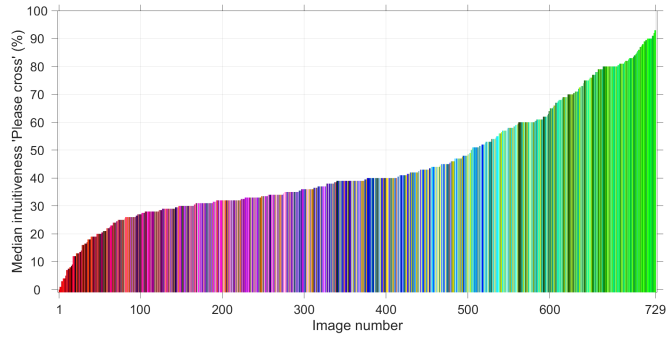

Fig. 2. Median intuitiveness ratings of each color for 'Please cross', sorted in ascending order (Experiment 1).

Table I. Colors yielding the highest intuitiveness for signaling 'Please cross' (Experiment 1)

Red	***Green***	***Blue***	***Median intuitiveness***
32	224	0	93
0	255	32	93
64	224	0	92
0	192	32	91
0	192	64	91
32	224	32	90
0	255	64	90
0	224	32	90
0	255	0	90
32	255	64	90
64	255	0	90
32	192	64	89
32	192	0	89
32	192	32	89
32	255	0	89

Besides median intuitiveness, it is of interest whether the intuitiveness ratings were consistent between participants. Fig. 3 shows the standard deviations (SD) of the intuitiveness of each color, sorted in ascending order. An interesting observation is that red yielded the highest SDs, indicating large individual differences. The highest SD (36%) was obtained for almost pure red (RGB 224, 0, 0). Cyan also yielded a relatively high SD (29%), and so did black (27%) and white (31%).

B. *Experiment 2 ('Please Do NOT Cross')*

A total of 2000 people participated between 14 April 2020 and 23 April 2020. The total cost was USD 600. The survey received a satisfaction rating of 4.3 on a scale from 1 ('very dissatisfied') to 5 ('very satisfied'). Using the same exclusion criteria as Experiment 1, 674 participants were removed, leaving 1326 participants.

The participants resided in 66 countries, with the most represented countries being Venezuela (N = 504), United States (N = 103), and Russia (N = 82). The sample consisted of 862 males, 460 females, and 4 participants who selected "I prefer not to respond" to the gender question. The mean age of the

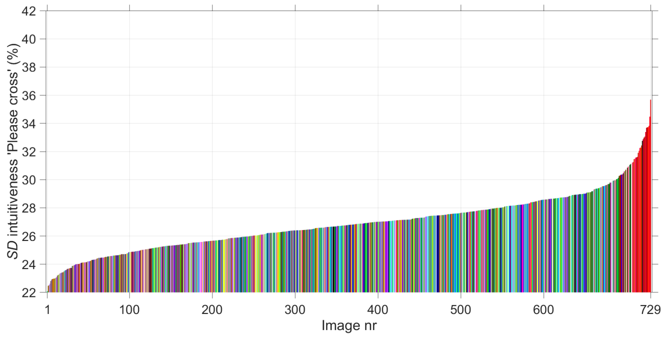

Fig. 3. Standard deviation of the intuitiveness ratings of each color for 'Please cross', sorted in ascending order (Experiment 1).

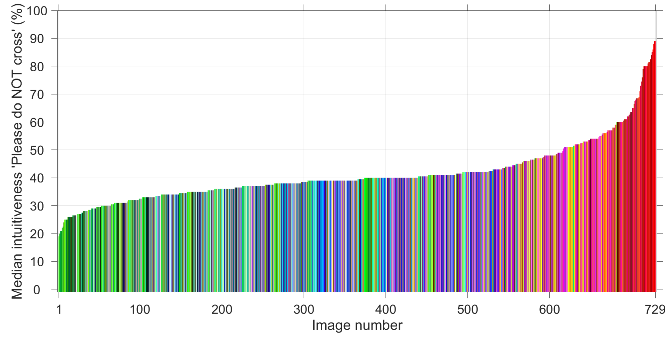

Fig. 4. Median intuitiveness ratings of each color for 'Please do NOT cross', sorted in ascending order (Experiment 2).

participants was 36.2 years (SD = 11.2). The participants took, on average, 21.4 min to complete the questionnaire and the experiment (median = 15.7 min). Of the 1444 participants in Experiment 1 and 1326 participants in Experiment 2, 871 participants had completed both experiments. Sixty-one participants were classified as colorblind, defined as entering an incorrect number or reporting 'no' in three or more of the five colorblindness items. Colorblindness was more common in men (5.6%) than in women (2.6%).

The color red was considered the most intuitive for signaling 'please do NOT cross' (Fig. 4). The highest median intuitiveness (89%) was obtained for almost pure red (RGB 224, 0, 0) (Table II) whereas the lowest intuitiveness was found for green (RGB 64, 255, 32). Low median intuitiveness was also observed for white (26.5%), black (29.5%), and cyan (39%).

In Experiment 1, red was regarded as non-intuitive for messaging 'please cross', with median ratings below 20%. One could expect the opposite results to be obtained for Experiment 2, with low intuitiveness ratings for green. However, as shown in Fig. 4, green was fairly intuitive, with most values around 20–30%; some shades of green yielded median intuitiveness ratings of 40% and even 60%.

The relatively high intuitiveness ratings for green can be explained by the SDs, as shown in Fig. 5. Green colors yielded high SDs, and so did red colors. In other words, although red was intuitive for most participants, some participants seemed to think that green was intuitive as a message for 'please do NOT cross'. Low SDs, on the other hand were found for turquoise (median = 37%, SD = 26%), amber (RGB: 255, 192, 0, median = 51%, SD = 27%), as well as purple (RGB: 128, 0, 128, median = 28%, SD = 26%), amongst other colors.

C. Robustness Checks

In this section, we examine whether the results are consistent for different subgroups. To this end, we used the Pearson product-moment correlation coefficient (r) of the median intuitiveness assessments. Since each participant rated a random 100 out of 729 colors, each color was rated by on only 13.7% of the participants on average. Before computing r, we first filled in missing data for each color, using the average intuitiveness ratings for similar colors (colors that were up to two steps away on the RGB spectrum, i.e., between 10 and 25

TABLE II. COLORS YIELDING THE HIGHEST INTUITIVENESS FOR SIGNALING 'PLEASE DO NOT CROSS' (EXPERIMENT 2)

Red	*Green*	*Blue*	*Median intuitiveness*
224	0	0	89
255	0	32	89
255	0	0	88
255	32	32	86
192	0	32	85
160	0	0	84
192	0	0	82
224	0	32	81
224	32	0	81
224	32	32	81
255	32	0	80
160	0	32	80
255	0	64	80
255	32	64	80
192	32	0	80

colors). Using this procedure, average data availability for each color increased from 13.7% to 94.4%.

- Men and women gave consistent median intuitiveness ratings in Experiment 1 (r = 0.99) and Experiment 2 (r = 0.97). The correlation for Experiment 1 is illustrated in Fig. 6. It can be seen that there is a strong congruence, with only a small deviation from the unity line. This deviation does not necessarily indicate a structural gender difference in color judgments, but may also be due to moderacy bias of men or a confounding effect with age or country of residence (e.g., women were

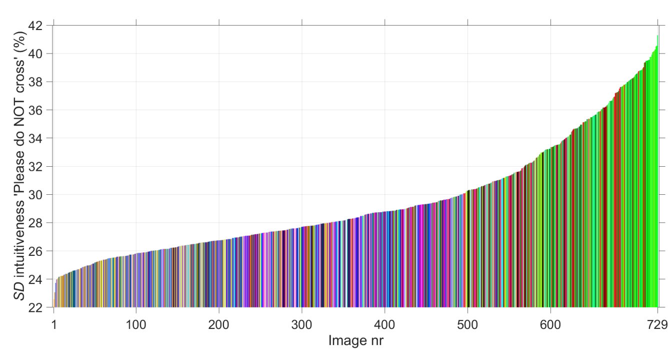

Fig. 5. Standard deviation of the intuitiveness ratings of each color for 'Please do NOT cross', sorted in ascending order (Experiment 2).

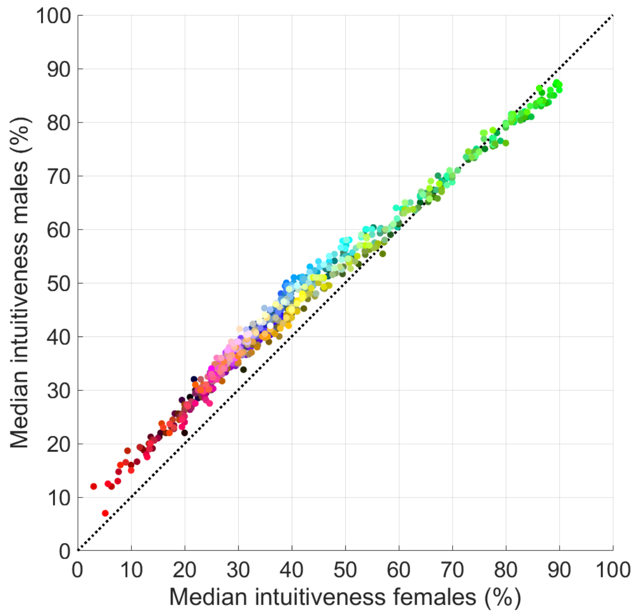

Fig. 6. Median intuitiveness ratings of males and females, for 'Please cross' (Experiment 1).

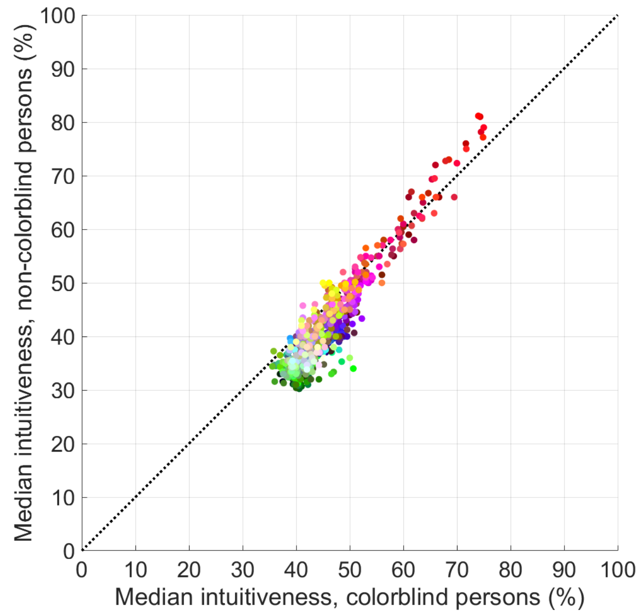

Fig. 7. Median intuitiveness ratings of colorblind and non-colorblind persons for 'Please do NOT cross' (Experiment 2).

overrepresented in some countries, while men were overrepresented in other countries).

- Participants who were colorblind and participants who had normal color vision yielded comparable median intuitiveness ratings ($r = 0.93$). However, the ratings for the colorblind persons were more compressed than those of the non-colorblind. Red-green colorblindness is the most common form of colorblindness, which might explain why colorblind people gave less extreme ratings for both red and green (Fig. 7).
- Participants from the two most highly represented countries (Venezuela and United States) provided similar median intuitiveness ratings in Experiment 1 ($r = 0.99$) and Experiment 2 ($r = 0.85$).
- Participants who completed both experiments and participants who completed only one of the two experiments provided similar median intuitiveness ratings in Experiment 1 ($r = 1.00$) and Experiment 2 ($r = 0.97$).

D. Illustration of Individual Differences

Experiment 1 showed that green was the most intuitive color for 'please cross' while Experiment 2 showed that red was the most intuitive color for 'please do NOT cross'. These findings indicate that participants generally used an egocentric rather than an allocentric perspective. Experiment 2 further showed large *SD*s for red and green.

To gain more clarity on these individual differences, we selected the 871 participants who completed Experiments 1 and 2, and then examined their intuitiveness ratings for red and green. More specifically, we calculated the mean intuitiveness for the 35 reddish colors that were up to four steps away from pure red, and for the 35 greenish colors that were up to four steps away from pure green. The results in Fig. 8 confirm our previous observation that, for Experiment 1, red was generally not intuitive and green was generally intuitive. For Experiment 2, however, there was a clear dichotomy, as indicated by the cross-like shape of the connecting lines: a large number of participants considered red as intuitive for not crossing (as mentioned), but a significant number of participants found green intuitive for not crossing. These findings illustrate the aforementioned egocentric-allocentric confusion, when the instruction is not to cross the road.

IV. Discussion

Our study is a significant step forward from previous research on eHMI color. First, our research focused not only on eHMI intuitiveness for signaling 'please cross' but also for signalling 'please do NOT cross'. Second, we did not use only two or three colors [6], [46]–[48], but no less than 729 colors.

A limitation of our research is that we used static stimuli. We have further disregarded factors such as eHMI visibility and attention-grabbing in environments where traffic may approach from multiple directions (e.g., [52]) or environments with visual distractions (see [53], for a recommended standardized test procedure for eHMIs). In addition, we have not investigated the extent to which different colors contribute to glare, nor have we investigated whether certain colors can be confused with each other in different environmental conditions, such as during the day versus at night (see, for example, [54], [55]). Furthermore, we used computer screens of participants all over the world, so no formal color management was used. Finally, our participants were relatively young, with an average age of 36 years. Whether the results are valid for older road users remains to be investigated.

Now that we have recognized the above strengths and limitations, the question is what color to use for eHMIs. Before answering this question, we first indicate what colors should *not* be used.

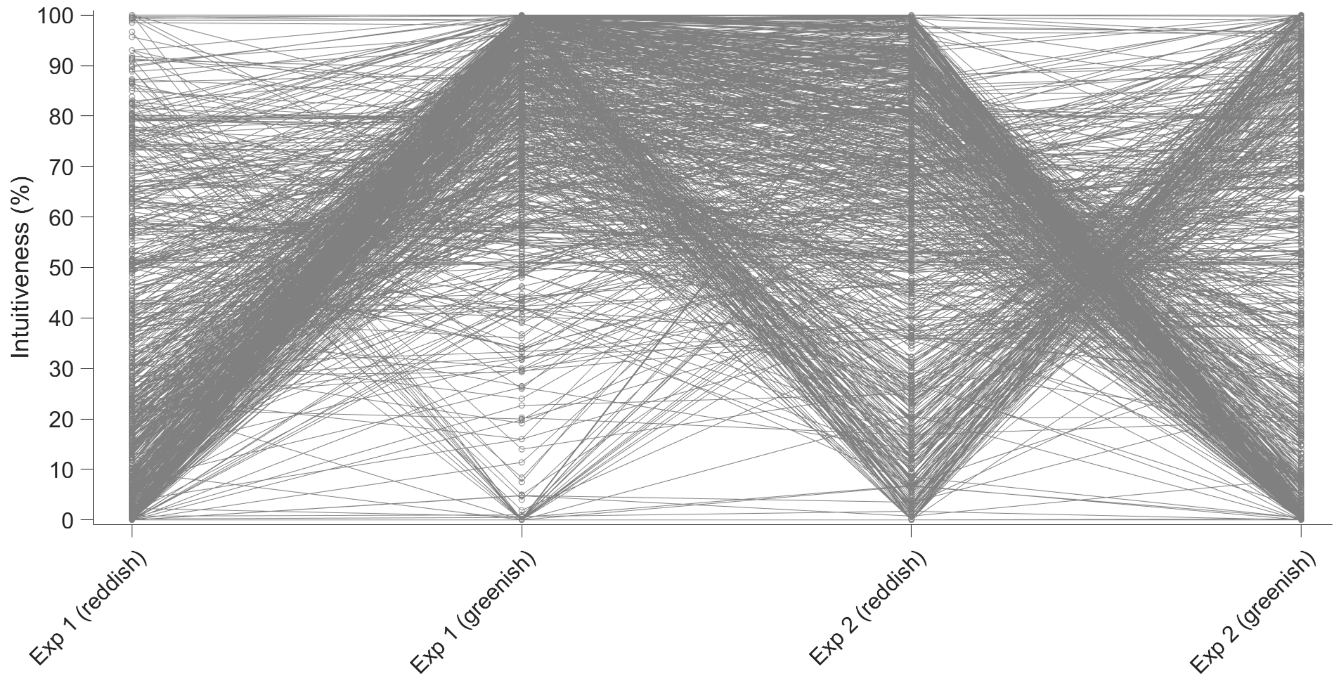

Fig. 8. Intuitiveness ratings for reddish and greenish colors for the 871 participants who completed Experiment 1 ('Please cross') and Experiment 2 ('Please do NOT cross'). The lines connect the intuitiveness ratings of the same participant.

- eHMIs that intend to signal 'please cross' should not be red. Red yielded the lowest intuitiveness ratings and the largest individual differences. In other words, red is not only non-intuitive for crossing but is also interpreted differently by different people. It is further noted that red eHMIs are probably not allowed in current traffic. In one of the patents presenting a front brake light, it is mentioned that the front brake light "can be of any desired hue, such as amber, green, aqua, magenta, etc. Red, however, is generally not permitted, as it would cause confusion with rear brake lights" [56].
- eHMIs that intend to signal 'please do NOT cross' should not be green. Green yielded low intuitiveness ratings (median mostly below 50%) and high standard deviations.
- eHMIs that intend to signal 'please do NOT cross' should not be red. Although red was generally the most intuitive color, it produced high standard deviations. This finding is consistent with the introduction, where we pointed to potential problems of egocentric-allocentric confusion. That is, some participants may have thought that a red eHMI is a front brake light that indicates that the pedestrian can cross. It goes without saying that if the eHMI tries to indicate that the pedestrian is not allowed to cross, but the pedestrian interprets this as 'please cross', dangerous situations can arise.

The above results seem robust for different subgroups, such as men versus women, colorblind persons versus non-colorblind persons, and individuals from the two most highly represented countries (Venezuela and the United States). The question remains whether an eHMI should be maximally intuitive (i.e., intuitiveness scores as close to 100% as possible), or in midrange instead (i.e., as close to 50% as possible). Dey et al. [47] seemed to be in favor of the midrange solution, as it "allows pedestrians the possibility to learn and assign a new meaning to it without leading to misunderstandings. This therefore leads to a recommendation that cyan may be well-suited for communicating a yielding message in eHMIs."

Our recommendation is that if the goal is to create eHMIs that convey a 'please cross' message, colors close to pure green should be used; these colors yielded the highest intuitiveness ratings and relatively small individual differences. However, if the message to be conveyed is 'please do NOT cross', neither green nor red are acceptable solutions. As pointed out by Dey et al. [47], a safe solution could be to use a design that is not intuitive or non-intuitive. The disadvantage of cyan is that in some cases it can be confused with green [46], [47]. Apart from the aforementioned cyan, amber ('selective yellow') seems to be a good option for signaling 'please do NOT cross'. However, Werner [49] argued that amber is already used in motor vehicles, and is not an attractive color, which may hinder the acceptance of automated vehicles. Several other colors exist. For example, Toyota [10] has used purple in eHMIs, which in our study was yielded moderate intuitiveness and relatively small individual differences.

Supplementary Material

Supplementary material that includes anonymized raw data, stimuli, and their description, questions used in the Appen for both experiments, and MATLAB code used for the analysis is available at https://doi.org/10.4121/12948650. Public repositories of the server-side code are available at https://github.com/bazilinskyy/colours-crowdsourced (Experiment 1) and https://github.com/bazilinskyy/colours2-crowdsourced (Experiment 2).

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