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RESEARCH ARTICLE

Colour blindness adversely impacts face recognition*

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ABSTRACT
Whether colour information contributes to the process of face recognition remains controversial. We examine this question here by evaluating the face recognition performance of individuals who are colour blind. Specifically, we compared the performance profile of colour blind and matched control individuals on a colour face recognition task where shape information was progressively degraded. The colour blind participants performed significantly more poorly than controls on this task, as revealed through multiple dependent measures. There was, however, no difference between these two groups on a standardized grayscale control task of face recognition, ruling out a generic face recognition deficit. These results both uncover a face recognition deficit in colour blind individuals and provide evidence for the contribution of colour to everyday facial recognition.

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Colour blindness; facial recognition; surface information; face identification; visual perception

Colour blindness is a relatively common condition, affecting up to 8% of males and .4% of females worldwide (Birch, 2012). Among the variants of colour blindness, red-green colour blindness is the most common, and, while this form of colour blindness is known to have significant effects on daily life (Tagarelli et al., 2004), it is not typically considered a serious impediment (Chan et al., 2014).

While much research into face recognition has focused on the use of shape information to identify faces, a few investigations have explored the role of colour or surface information (Liu & Wechsler, 2001; Troje & Bülthoff, 1996). For example, when required to match contrast-negative faces that varied either in pigmentation or shape, observers did more poorly when the faces varied in pigmentation but not when they varied in shape (Russell et al., 2006). Consistent with this, when other cues, such as shape, are restricted, surface information can be utilized to support face recognition (Vuong et al., 2005; Yip & Sinha, 2002). Last, and of relevance to the current study, colour information is considered informative for discriminating between sex and between individual face identities (Elliot et al., 2010), and red and green colour information is especially useful (Nestor & Tarr, 2008a). Interestingly, in ventral visual cortex, the pre-eminent neural structure associated with face recognition, there are multiple colour-biased regions, and these are anatomically yoked to patches of neurons that respond selectively to face stimuli (Lafer-Sousa & Conway, 2013), suggesting that neurons that respond to coloured input may be co-activated or simultaneously recruited in response to face input.

Together, these findings lead to a clear prediction: if colour information, especially red and green information, plays a necessary role in face recognition, then red-green colour blind individuals should be impaired in face recognition. We examined this prediction in a group of colour blind individuals on an experimental face recognition task where pixels in the faces were progressively scrambled. The logic of the manipulation is as follows. In this task, scrambling pixels randomly throughout the face alters the distribution of surface colour information available on the face without removing colour from the display. Small lines that make up local contours that serve as cues conveying shape information, such as the local contours of the eyes and mouth, are likely to be degraded most quickly under the scrambling manipulation. In contrast, large areas of uniform colour such as that associated with surface cues like the colours of the lips, the eyes, and the cheeks (Nestor & Tarr, 2008b), are relatively less impacted (see Figure 1(B) for examples of scrambling). Importantly, the overall colour of the face remains

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Figure 1. (A) The six individual faces used in the staircase assessment of recognition and (B) A single face shown with various levels of pixel scrambling: 30% (left), 60% (middle), and 90% (right) pixel scrambling.

constant even at 100% pixel scrambling, when there is no obviously discernible shape information remaining. Therefore, while colour and shape information are both degraded within this experiment, shape information is degraded much faster and obscured to a greater degree than is the surface property of colour. The premise of this experiment comes from studies which have adopted a similar approach. For example, in one such study, Nestor and Tarr (2008b) used very blurred images of MPI faces and asked participants to judge face gender. They noted that observers turn to diagnostic surface properties, including colour, when the reliability of shape cues is compromised (see also Tarr et al., 2001).

This scrambling manipulation allows us to study the effects of progressive shape degradation on face recognition. If colour information plays an important role in face recognition, then colour blind individuals should perform more poorly than non-colour blind individuals on this task, especially at higher levels of pixel scrambling when shape information is even more degraded relative to colour information. If colour blind individuals do perform more poorly than the controls, this would suggest both that colour plays a necessary role in face perception and that colour blindness may be more disadvantageous in daily life than has been considered thus far.

Methods

Participants

The participants were 17 self-reported colour blind participants, as well as 19 matched, normal-sighted individuals. Consistent with the higher frequency of colour blindness in males, the colour blind group consisted of 16 males and 1 female, aged 18–41 years (M = 22.74, SD = 4.52). Control participants consisted of 11 males and 8 females, aged 18–35 years (M = 26.41, SD = 7.48), and there was no significant difference in age between the two groups (two-tailed t-test: $t(34) = -1.81$, $p = .080$). All individuals had normal or corrected-to-normal visual acuity by self-report, and all provided consent to participate. The protocol was approved by the Institutional Review Board of Carnegie Mellon University and participants received $10 or class credit upon completion of the study.

Ishihara Plate evaluation of colour blindness

To evaluate the nature and severity of colour blindness and to ensure the appropriateness of participant inclusion, ten images were chosen from the well-known Ishihara colour blindness screening test and presented individually with unlimited exposure duration. The participant was required to report the number embedded in the display. The number of correct digit reports, typical red-green colour blind responses, and any atypical responses were recorded for each participant. Colour blind participants performed significantly more poorly than the control individuals (two-tailed t-test: $t(34) = 9.84$, $p < .00001$, $\eta_p^2 = .740$). Colour blind participants averaged 4.82 out of 10 correct answers (SD = 2.01), while controls averaged 9.63 out of 10 correct answers (SD = .684). All colour blind participants provided error responses consistent with partial red-green colour blindness, typically including several red-green confusions as well as some otherwise abnormal responses, while controls indicated no red-green confusions, although in a few individuals there were up to two abnormal responses.

Cambridge face memory test

Having ensured that the experimental participants met the criterion for colour blindness, all participants then completed a standardized face recognition test, the Cambridge Face Memory Test (CFMT). Normal accuracy on this test would rule out prosopagnosia or other non-colour visual impairments as a possible explanation for any deficit we might observe in the colour blind group. The CFMT, an on-line test of face recognition using grayscale faces, has been described in detail previously (Duchaine & Nakayama, 2006). Briefly, participants studied faces of 6 individuals in frontal and profile views. In the first phase, subjects indicated which of three displayed faces was studied. The task remained the same in the remaining phases, but, in phase two, the studied face was shown in a different pose or with different lighting. Last, in the third phase, the studied face had Gaussian noise added to the images. There were no significant differences between the groups on any of the CFMT phases or on the overall CFMT performance (colour blind: $M = .789$, $SD = .145$, control: $M = .791$, $SD = .108$, two-tailed t test: $t(34) = .063$, $p = .951$). These findings confirm the absence of prosopagnosia or other perceptual difficulties in the colour blind group.

Stimuli and apparatus

Participants sat in a quiet, darkened room, approximately 60 cm from a 2016 MacBook computer with a 12″ screen and a resolution of 2304 × 1440, running MATLAB version R2018a. The stimuli were colour images of six adult Caucasian males selected from the Radboud database (Langner et al., 2010). We specifically adopted a set of homogeneous faces from which to probe the role of colour in individual identity recognition. As evident from the images shown in Figure 1(A), the faces were of frontal views of young adult males, with no significant facial hair or obvious blemishes, and with a neutral facial expression, frontal gaze and illumination. These images were scaled uniformly and aligned with roughly the same position of the eyes and nose, cropped to show only internal features of the face, and normalized with the same mean and root-mean-square (RMS) contrast values for luminance. These manipulations constrained the amount of shape information available within the images.

Procedure

At the outset of this experiment, to acquaint participants with the stimuli, all six intact faces were shown simultaneously on the computer screen, with two rows of three faces, centred in the middle of the screen. Thereafter, task instructions were provided: participants were told that they were to complete a one-back task and indicate whether the currently displayed face was the same as or different from the previous face (i.e., whether two consecutive face stimuli were identical or not), by pressing the "s" key if the stimuli were the same or the "d" key if the stimuli differed. The participant's understanding of the instructions was confirmed by providing practice trials as follows. Intact faces were presented: on 30% of the trials, the two sequentially presented faces were the same and, on the remaining trials, the faces differed. Each face was shown at least once in each run, and if the participant made any errors in a given run, the same one-back procedure was repeated for up to a total of ten runs. If after these ten runs the participant had still not successfully mastered the task, the training was terminated and the participant was excluded from the next testing stage. Two participants, one control individual and one colour blind individual, failed to master this task and were excluded from further participation and all analyses.

The testing phase of the experiment also consisted of a one-back test, but in the context of a staircase threshold procedure (see Figure 2). On the first trial, one face, randomly selected from the set of six stimuli, appeared in the centre of the screen for one second and was followed by an inter-trial interval of a blank screen for one second. Immediately thereafter, another face was shown at the same screen location, and remained visible until a same/different response was provided. On 25% of the trials, the two sequentially presented faces were the same; on the remaining trials, the faces differed.

The staircase method proceeded as follows: noise was introduced by scrambling a percentage of pixels

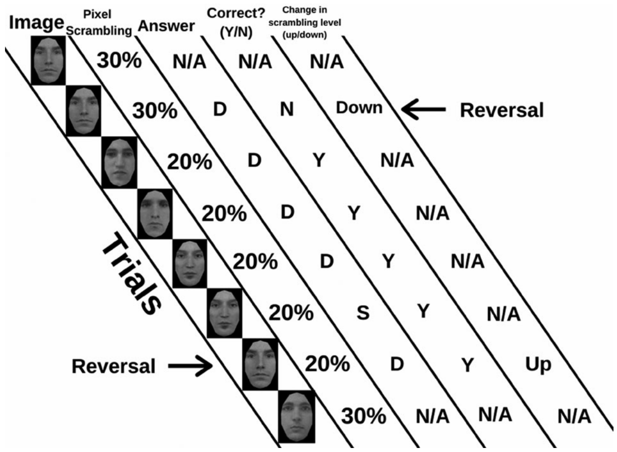

Figure 2. A schematic depiction of the staircase facial recognition task showing an image and level of scrambling as well as the participant's response and the change in scrambling level; "S" indicates an answer of "same", while "D" indicates an answer of "different". N/A refers to "No Answer" or "Not Applicable". Faces were coloured within the actual experiment.

randomly within the faces, ranging from 0% scrambled to 100% scrambled (see Figure 1(B) for examples). The initial face was always presented at 30% scrambled, and then, upon an incorrect response (miss or false alarm), the scrambling decreased by 10 percent. The scrambling was increased by 10% following five correct responses (hits or correct rejections). The procedure continued until participants had reached a total of 30 reversals (changes in the difficulty level back and forth) (see Figure 2). Participants' scrambling levels tended to even out as participants became more comfortable with the task, and were quite stable within the last 8 reversals. We obtained three dependent measures on the staircase colour recognition task: the lowest percent of scrambling reached ("minimum scrambling", between 0 and .3), the scrambling threshold ("threshold", the average of the last 8 reversals, between 0 and 1), and the highest percent of scrambling reached ("maximum scrambling", between .3 and 1) (see Figure 3).

Results

To ensure that the mixed-sex control group were well matched to the mostly male colour blind individuals, we performed an initial analysis only on the control data. Given that there was no sex difference on the scrambling threshold (male: M = .594, SD = .217, female: M = .598, SD = .196, two-tailed *t*-test: $t(17) = -.041$, $p = .968$), we collapsed the data from the male and female controls for comparison with the colour blind individuals.

As evident from Figure 3, the colour blind participants reached a significantly lower maximum level of scrambling (M = .718, SD = .189) than control participants whose performance remained good even when approaching 100% scrambling (M = .926, SD = .099) (two-tailed t-test: $t(34) = 4.232$, $p < .001$, $\eta_p^2 = .345$). This finding indicates that the control participants were able to tolerate higher levels of scrambling and still respond accurately compared to the colour blind participants. Consistent with this, the colour blind participants' performance reached a lower scrambling threshold (M = .450, SD = .180) than control participants (M = .596, SD = .203) (two-tailed *t*-test: $t(34) = 2.260$, $p = .030$, $\eta_p^2 = .131$). Last, the colour blind participants reached a significantly lower minimum level of scrambling (M = .129, SD = .126) than control participants (M = .221, SD = .113) (two-tailed *t*-test: $t(34) = 2.294$, $p = .028$, $\eta_p^2 = .134$).

Discussion

In order to elucidate the role of colour information on face recognition, we characterized the performance of red-green colour blind individuals on a task of face recognition. The major finding was that the colour blind individuals performed more poorly than the control participants on a sequential face discrimination task in which the overall colouration of the image was held constant, but the pixels were increasingly scrambled across the surface of the face. Of note, the colour blind individuals performed significantly worse than the controls on even the lowest levels of pixel scrambling in this task, revealing that the poorer performance in the colour blind individuals could be elicited with relatively minimal shape degradation (see "Minimum", Figure 3).

The poorer performance of the colour blind individuals relative to the controls could not be accounted for by a problem with the discrimination of faces in general given that their performance did not differ from that of the controls on the standardized CFMT. Additionally, because both the CFMT and the colour threshold task included a memory component, but the two groups performed differently only on the colour threshold task, we can rule out a problem of face memory storage or retrieval in the colour blind

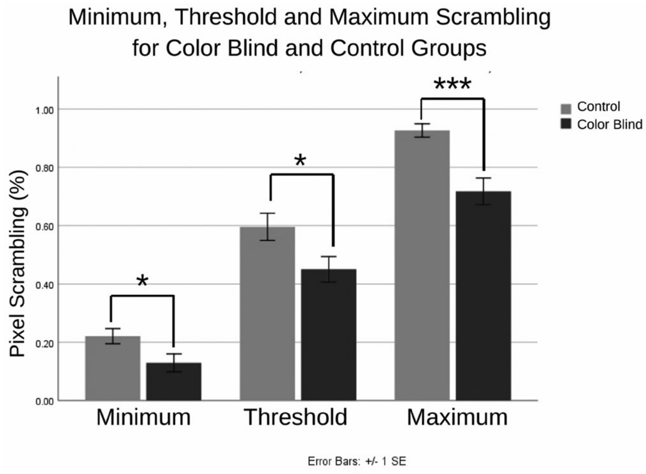

Figure 3. Percent of pixel scrambling (and 1 SE) for minimum, threshold and maximum scrambling levels for colour blind and control groups. Higher bars indicate better performance. (*$P < .05$; **$P < .01$; ***$P < .001$).

group. The significantly poorer performance of the colour blind individuals likely resulted from their inability to discriminate faces under conditions of shape degradation. Whereas the control participants could still discriminate faces even under markedly degraded conditions presumably by disproportionately relying on the colour information, especially associated with parts of the face with large surface area such as eyes, lips or cheeks, (Nestor & Tarr, 2008b), as shape information was increasingly occluded, this was not true for the colour blind participants.

That the colour blind participants were adversely affected under conditions when colour information was still useful suggests that colour likely plays a critical role in face recognition. Although naturalistic daily encounters requiring face recognition do not usually entail such obvious degradation as that adopted here, there are multiple ways in which face shape may be naturalistically degraded including, for example, when faces are partially obscured or viewed from unusual perspectives (e.g., in profile), or when individuals possess similar facial structures. It is under such conditions that colour may be especially relevant and colour blind individuals may suffer disproportionately.

One might ask specifically what role colour plays in face recognition. In addition to conferring a recognition advantage over monochrome displays of faces (Nestor & Tarr, 2008a), colour is assumed to be especially important when shape cues are progressively degraded. Indeed, Yip and Sinha (2002) showed that, as image resolution was reduced, face recognition was adversely affected for grey-scale, but not for colour, images. They concluded that colour information aids in low-level image segmentation: because many facial landmarks can be defined by hue (and luminance) changes, colour information can assist by recovering geometric contours that separate out facial landmarks such as the mouth and eyes. Thus, colour can aid segmentation by determining and then demarcating region boundaries. Nestor and Tarr (2008b) also provide evidence supporting the role of segmentation and argue further that colour information encoded by the three colour perceptual channels likely exploits feature contrast, especially around the cheeks and chin areas, and that this information is useful for gender discrimination as well as individual recognition.

Together, these findings confirm that colour information (and perhaps, disproportionately red and green) play a greater role in face recognition than previously considered. Under conditions of visual stress, it is likely that colour blind individuals will fare more poorly than their non-colour blind peers, and, although not trivial to execute, further research should evaluate the extent to which colour blindness impacts face recognition in daily life. We note that further studies on this topic might make use of an actual face recognition task, perhaps with both familiar and unfamiliar faces, so as to evaluate the impact of colour blindness in the context of a more ecologically relevant task. Furthermore, evaluating the performance of colour blind individuals with a diverse set of faces (female and male, faces of other races) will provide further insights into the performance profile of colour blind individuals and advance our understanding of the utility of colour in face perception.

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