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RESEARCH ARTICLE

Categorical color perception shown in a cross-lingual comparison of visual search

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Abstract

Categorical perception (CP) for colors entails that hues within a category look more similar than would be predicted by their perceptual distance. We examined color CP in both a UK and a remote population (Himba) for newly acquired and long-established color terms. Previously, the Himba language used the same color term for blue and green but now they have labels that match the English terms. However, they still have no color terms for the purple areas of color space. Hence, we were able to investigate a color category boundary that exists in the Himba language but not in English as well as a boundary that is the same for both. CP was demonstrated for both populations in a visual search task for one different hue among 12 otherwise similar hues; a task that eliminated concerns of label matching. CP was found at the color-category boundaries that are specific to each language. Alternative explanations of our data are discussed and, in particular, that it is the task-dependent use of categorical rather than non-categorical (perceptual) color networks which produces CP. It is suggested that categorical networks for colors are bilaterally represented and are the default choice in a suprathreshold similarity judgment.

KEYWORDS

categorical perception, color, cross-lingual, visual search

1 | INTRODUCTION

Color terms affect performance on many color similarity judgments[1] but definitely not on all such tasks.[2–6] Similarly, while one's native language can promote access to visual consciousness in some color tasks,[7] it is not agreed that it affects subjective experience of colors in other tasks.[1] However, the subjective appearance of color is our current concern. In particular, we are concerned with the effect of subjective appearance known as categorical perception (CP) described by Harnad.[8] CP means that stimuli within a category look/sound more similar to each other and that stimuli from different categories look/sound more different than would be predicted from their perceptual distance. The most pronounced case of CP is in speech perception where all the members of a category can even sound identical.[9,10] For color CP, the claim is that hues with the same name just look more similar to each other[11] as, somehow, labeling causes the perceptual warping within the color category.[1,11–13] More

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recently, References 4,14 have proposed an alternative model of CP called cognitive facilitation where effects are limited to category boundaries.

To some, CP is a cornerstone of visual perception[15,16] but any claim that might be seen as showing thought or language influencing perception (cognitive penetrability) has been fiercely contested.[17,18] Firestone and Scholl[17] would argue that to find CP is paradoxical if the stimuli are already equally spaced as for instance they are in the Munsell system to be used in our study. Their argument goes that a color difference cannot both be equal and not equal at the same time. However, long ago, Kay and Kempton[12] argued that the observer can take either a perceptual or a categorical stance in making a color judgment. In their study, observers carried out two tasks with the same stimuli, one that favored perceptual discrimination and the other categorical discrimination. CP was only found in the latter. So, it is not necessarily paradoxical to find CP and we will contribute to this issue primarily by providing reliable evidence for color CP from a cross-lingual analysis (see Reference 19).

We will examine a language (Otjihimba) with different numbers of color terms to English and where CP has been aligned to the presence of a color term in that language.[20] When tested by Roberson et al.,[20] Otjihimba had only five basic color terms (*serandu, burou, vapa, dumbu, zoozu*). In common with many others, it was a “grue” language where the same word is used for *blue* and *green* terms. Unlike for Western populations, the Himba did not show CP for *blue* or *green* colors though they did for their own color terms. However, CP in Roberson et al.[20] was obtained from a short-term memory paradigm and thereby contained the potential for naming artifacts.[21–23] Besides the obvious concern that it is name memory rather than perception that is being examined, there is the possibility of an inconsistent use of category labels depending on a hue's position in a category[24] though note the counter evidence in Best and Goldstone.[25] At the very least, name matching artifacts can be avoided if we use a visual search paradigm where the task is to find the odd-one-out that is different from other colors;[26–32] such tasks can be performed very quickly.[33] The odd-one-out in our task is either from the same or different color category to the identical colors. CP is observed if quicker responses are found when the odd-one-out is from a different category. In the visual search task, naming individual colors to find the odd-one-out would be ineffective as correct responses are typically given with latencies of not more than 1 s.

Our previous Himba naming data were collected in 2004. Since that time, the Himba have had more contact with urbanized communities. Indeed, we have documented the cognitive changes induced by that contact.[34–38] We have even noted the effects on similarity judgments of just a few visits to a small town.[39] There was reason to suspect from a brief report[3] that greater contact with other cultures had also led to an enlargement of the Himba color lexicon. We now know that is the case and have recently reported that Otjihimba can be regarded as a seven-color term language (*serandu, burou, grine, vapa, dumbu, zoozu, and vinde*) where both new terms have probably been imported from Herero where these terms have a European origin,[40] unlike English which can be regarded as a language with 13 terms.[41] English terms consist of 11 (*black, white, red, blue, green, yellow, orange, purple, brown, pink, gray*) regarded as basic for some time[42,43] with the recent additions of *lilac* and *turquoise* that also cannot be subsumed by another term.[41] It is important to note that while Otjihimba terms can be translated by English terms, they cover a more extensive area in color space than those English terms.[40] For our study, this is of particular importance for *serandu* which we could gloss as “red” and *burou* that we could gloss as “blue.” In Otjihimba, there is a boundary between *serandu* and *burou* but there is no boundary in English between *red* and *blue* because of *purple* terms; so, we will from now on not use gloss terms.

A requirement for conducting studies of CP is that color categories occupy sufficient areas of color space to allow pairs of stimuli to be discriminable but still be within the same color category. So, it is not surprising that most of the research with CP has used *green* versus *blue* as those colors occupy around half of color space. Our predictions, from the new color naming data, were that for both Otjihimba and English speakers a green stimulus would be more easily found among blue distractors but not so readily if the green stimulus was among other green stimuli. A similar prediction would be for quicker detection of a *blue* stimulus when it is among cross-category (*green*) stimuli but not so readily if it is among within-category (*blue*) stimuli. However, the predictions were different for other color categories, specifically within the *serandu* and *burou* denotations of color spaces. In Otjihimba, the color area *serandu* has a boundary with *burou*. In English, there are many names (*blue, lilac, pink*, and *purple*) for the colors around the *serandu/burou* boundary; because of this it is only Otjihimba that has a within-category condition. CP is predicted for both populations for the colors used in the Otjihimba cross-category condition but the within-category condition would be different. The Himba should find their within-category search harder than the UK population.

2 | METHODS

2.1 | Participants

Forty-three native Himba speakers (30 female, 13 male) aged between 15 and 44 years, with a mean age = 23.63, SD = 7.77, from remote villages in north-west Namibia completed the experiment. One further participant did not complete both tasks. None had taken part in any other study. Participants were compensated for their time with gifts of sugar and flour. The study received ethical approval from Goldsmiths University of London (No1390, June 4, 2018). Further information on Himba cognition is available in Trémolière et al.[44] Each observer carried out the visual search task for both *blue/green* and *serandu/burou* boundaries.

Different UK observers carried out the two tasks. For the *blue/green* search, the data from Davidoff et al.[2] consisting of 14 participants (10 female, 4 male) aged between 19 and 38 years, with a mean age of 23.86 years, SD ≈ 4.75 recruited at Goldsmiths, University of London were combined with 14 (2 male, 12 female) new observers aged between 19 and 21 years, with a mean age 20.26 years, SD = 0.83, recruited from the University of East London. For the *serandu/burou* search, a further 43 participants (15 male, 28 female, aged between 18 and 59 years, with a mean age of 29.79 years, SD = 9.71), were recruited at the University of East London (Ethics approved by the University of East London Research Ethics Committee). All UK participants were native English speakers, reported normal or corrected to normal vision, and had normal color vision as tested using the Ishihara[45] plates for red-green color vision.

2.2 | Stimuli and Materials

Previous studies with the Himba, like for other populations in the World Color Survey,[46] assessed color judgments by presenting Munsell chips under controlled illumination. However, doubts have been expressed about the spacing of *green* and *blue* colors in Munsell space that has been commonly used in these studies and also about the control of the color reproduction.[27,31,47–49] To respond to these criticisms, we used the same calibrated monitor to present our color stimuli in both UK and Himba participants ensuring that the differences between measured colors across and within categories were equivalent using the current recommended CIE ΔE2000 color difference formula. All stimuli were presented on a 13″ Apple MacBook Pro (mid-2010) and responses were collected using an external number pad. To maintain the consistent color appearance of the simulated Munsell chips on the digital display that supports the widely used D65 standard white point of sRGB, we adapted the xyY (1931) coordinates of the simulated Munsell chips from Illuminant C to D65. We also calibrated the monitor toward D65 in accordance with sRGB and confirmed that the reproduction of the intended and achieved color stimuli was within the invisibility error threshold, assuming a just-noticeable difference of 1 ΔE_{00} in CIELAB. The measured CIE 1931 chromaticity coordinates of the white point of the monitor was $x = 0.3116$, $y = 0.3274$ with a correlated temperature of 6581 K and luminance of 160 cd/m^2. Repeating the spectroradiometric measurements of the monitors after the fieldwork showed only a minimal drift of the white point over time (<0.003). The stimulus presentation was controlled by PsychoPy v.1.90.2 software.[50]

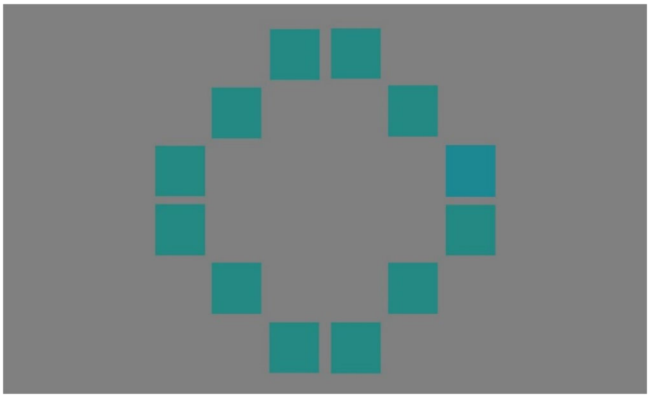


FIGURE 1 Example stimulus display. Here the target is on the right-hand side of the screen.

There were two sets of stimuli, one for each boundary tested (*blue/green* and *serandu/burou*). Each set consisted of four pairs of stimuli; for the Himba there were two cross-category pairs and two within-category pairs for both boundaries. For English speakers, it was the same for the *green/blue* boundary, but all comparisons were cross-category pairs for the *serandu/burou* search task. All stimulus displays consisted of 12 square (2.15°) color patches arranged as in an offset clock face (see Figure 1) in which 11 of the colors were identical and one was an odd-one-out. Across the experiment, each stimulus in a pair was presented as either the target odd-one-out (appearing in each of the 12 possible positions) or as the surrounding distractors in random order. Color stimuli for all visual search tasks were presented against a neutral gray background with luminance of 38 cd/m^2.

The *blue-green* boundary was placed at 6.25BG,[2] with each stimulus in a pair separated by 5 Munsell steps and pairs evenly arranged around the boundary, as can be seen in Figure 2A. The two cross-category pairs were 5BG–10BG, and 2.5BG–7.5BG. The two within-category pairs were 8.75G–3.75BG and 8.75BG–3.75B. All were presented at equal Value = 5 and Chroma = 6. The mean color difference between stimuli was $\Delta E_{00} = 6$, STD = 1. None of the stimuli were repeated across category conditions. The Otjihimba boundary between *burou/grine* is at the same place as the English *blue/green* boundary.[40] A note needs to be added about these stimuli given that a *turquoise* term is becoming more common in

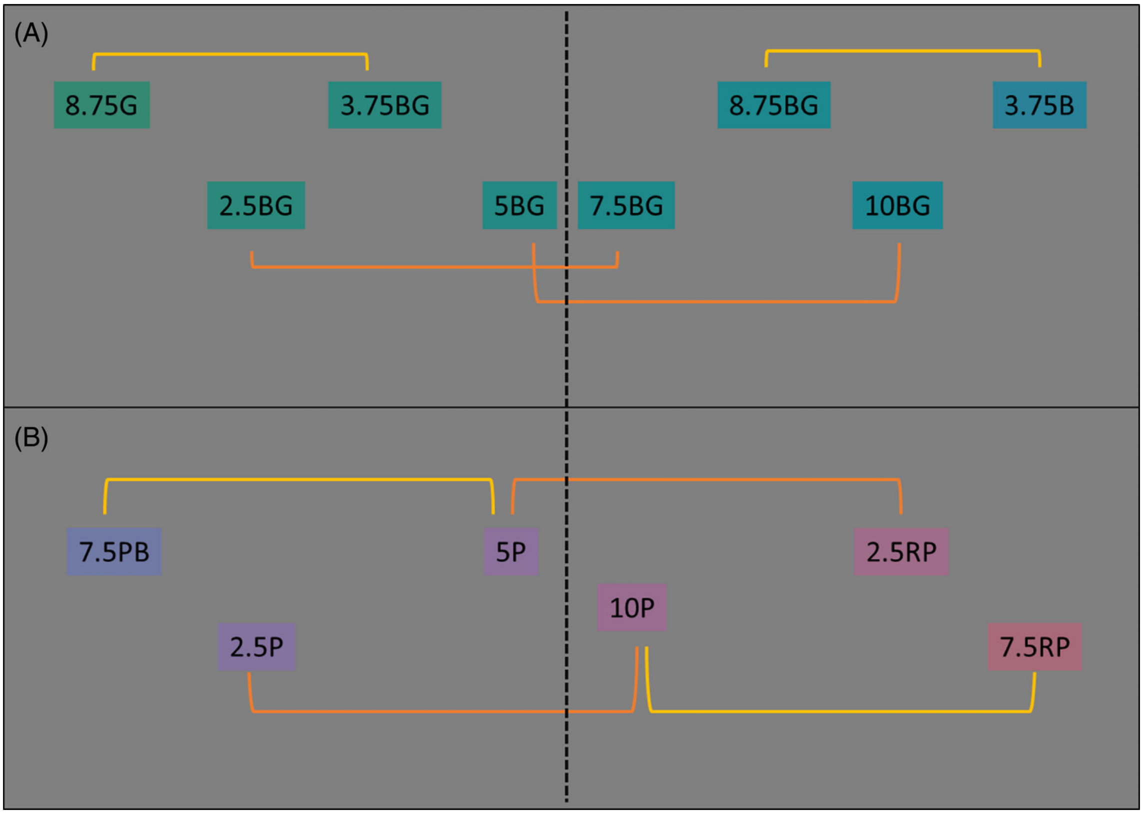


FIGURE 2 (A) Top panel shows stimuli in Munsell notation for tests across the *blue-green* boundary, and (B) Bottom panel shows stimuli for the *serandu/burou* boundary tests. Within-category pairs for the Himba are indicated by yellow lines and cross-category by orange lines. The same applies to English speakers for the *blue-green* boundary but all pairings are cross-category for them for the *serandu/burou* boundary (see Figure 3). The boundary between categories is shown with a black dashed line.

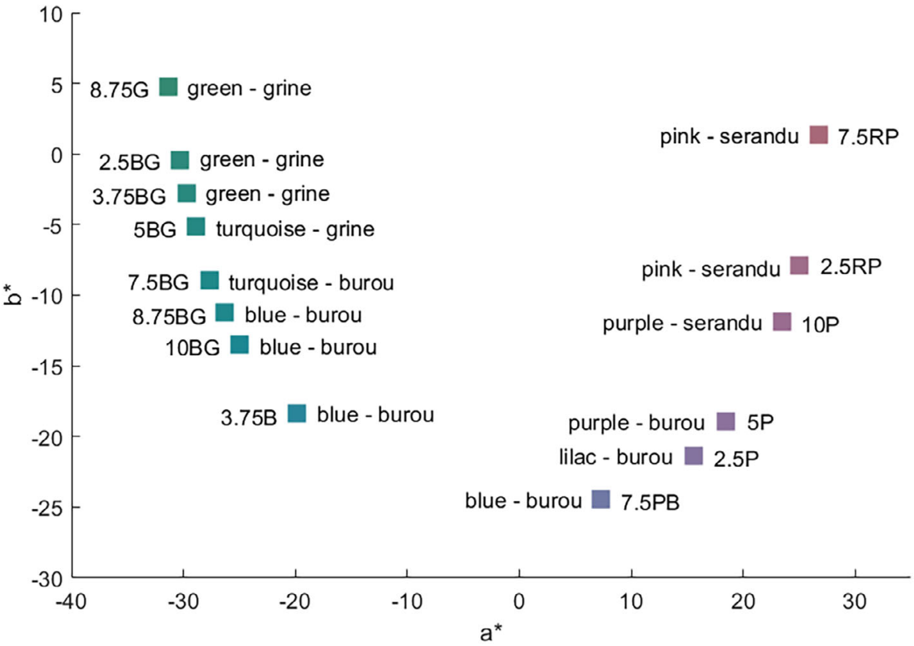


FIGURE 3 Color stimuli for tests across the *serandu/burou* boundary in a* b*plane of CIELAB with Munsell hue notation and estimated color names in English[51] and Otjihimba.[40]

English ([41]; see also[52]) and in other languages.[31,43,53] It might have been that the 5BG and 7.5BG samples could be called *turquoise* in English by some of our observers but we did not establish whether that was the case. However, our pairings of stimuli have been chosen so that whether they are both called *turquoise* or one *green* and the other *blue*, the pairings used are cross-category for English speakers.

The *serandu/burou* boundary was placed at 7.5P[40] with each stimulus in a pair separated by 7.5 Munsell steps and pairs evenly arranged around the boundary, as can be seen in Figure 2B. For the Himba, the two cross-category pairs were 5P–2.5RP and 2.5P–10P. The two within-category pairs were 5P–7.5 PB and 10P-7.5RP. Here we used only 6 different colors with the two stimuli closest to the boundary (5P and 10P) used in both cross and within conditions. The mean color difference between stimuli was $\Delta E_{00} = 9$, STD = 1. All were presented at equal Value = 5 and Chroma = 6. Figure 3 shows that the naming of the colors is quite different for English speakers.[51] 7.5 PB is called *blue*, 2.5P is called *lilac*, 5P and 10P are called *purple*, 2.5RP and 7.5RP are called *pink* though we did not examine the particular names given by our UK participants. Nevertheless, it can be assumed that, all combinations used with the *serandu/burou* boundary are cross-category for English speakers.

2.3 | Procedure

The visual search procedure was based on that of Davidoff et al.[2] and Gilbert et al.[29] Each trial started with a fixation cross for 1000 ms, followed by the stimulus display of 12 color patches in an offset clock-face arrangement. Participants were asked to decide whether the odd-one-out was on the left- or right-hand side of the screen with a corresponding button press on the number pad. The stimulus display remained on the screen until response, which then initiated a blank screen presented for 250 ms, followed by the next trial. Only responses under 2 s were included in analyses.

Each stimulus in a pair was presented as a target and distractor equally often, in each of the 12 possible locations, in random order. Thus, each block consisted of 96 trials; participants completed three blocks with short self-paced intervening breaks. A practice block of 8 trials using red [255, 0, 0] and yellow [255, 255, 0] stimuli ensured that participants understood the task. All testing was carried out individually, in a testing tent, under conditions of natural light for the Himba, and in a laboratory for UK participants. Himba participants carried out both tasks with alternate participants doing each visual search task first. The anonymous datasets generated during the current study are available online in the Open Science Framework (OSF) Repository of the Center for Open Science [Available at: https://osf.io/nkruh/?view_only=e93c3fbccaba4f638a27a778ec410bf1].

3 | RESULTS

Analyses were carried out separately on the *green/blue* and *serandu/burou* data. Stimulus separation in the *green/blue* task was smaller and produced longer latencies for both groups of observers. Only the RTs for correct responses were included. For the *green/blue* task, the overall accuracy for the UK participants ($N = 28$) was 0.99 (within category accuracy (M = 0.98, SD = 0.03); cross category accuracy (M = 0.99, SD = 0.02)) and for the Himba participants overall accuracy was 0.96 (within category accuracy [M = 0.96, SD = 0.09]; cross category accuracy [M = 0.96, SD = 0.08]). For the *serandu/burou* task, the overall accuracy for the UK participants was 0.99 (within category accuracy [M = 0.99, SD = 0.02]; cross category accuracy [M = 0.99, SD = 0.01]) and for the Himba participants overall accuracy was 0.96 (within category accuracy [M = 0.96, SD = 0.09]; cross category accuracy [M = 0.96, SD = 0.09]).

Data from participants with accuracy less than chance (50%) in any condition were excluded from further analyses but this applied to only one Himba participant.

3.1 | *Green/blue* visual search

The data from the new 14 UK participants and those from Davidoff et al.[2] were submitted to a mixed 2 × 2 ANOVA with between-participants factor Group (Old data, New data) × within-participants factor Category (Cross, Within). Consistent with the previous analysis, there was a statistically significant main effect of Category, $F(1, 26) = 99.55$, $p < 0.001$, $\eta_p{}^2 = 0.793$, with cross-category RTs (M = 0.868 s, SE = 0.033) faster than within (M = 0.972 s, SE = 0.32) but the main effect of Group was not statistically significant, $p > 0.1$, and neither was the interaction between Group × Category, $p > 0.4$.

Having confirmed that there was no difference between the new and old UK participants, data were combined in an ANOVA comparing UK with Himba participants. A mixed 2 × 2 × 2 ANOVA with between-participants factor Group (Himba, UK) × within-participants factors Category (Cross, Within) and Presentation side (left, right) was performed on the RT. We included side of presentation because of reports of greater CP in the right visual field.[29,54] There was a significant main effect of category, $F(1, 69) = 284.08$, $p < 0.001$, $\eta_p{}^2 = 0.805$, with cross-category RTs (M = 0.900 s, SE = 0.022) faster than within (M = 1.014 s, SE = 0.23) (Figure 4). The other main effects (including Group, $F(1, 69) = 2.84$, $p = 0.096$) interactions did not reach statistical significance, all other *ps* >0.16.

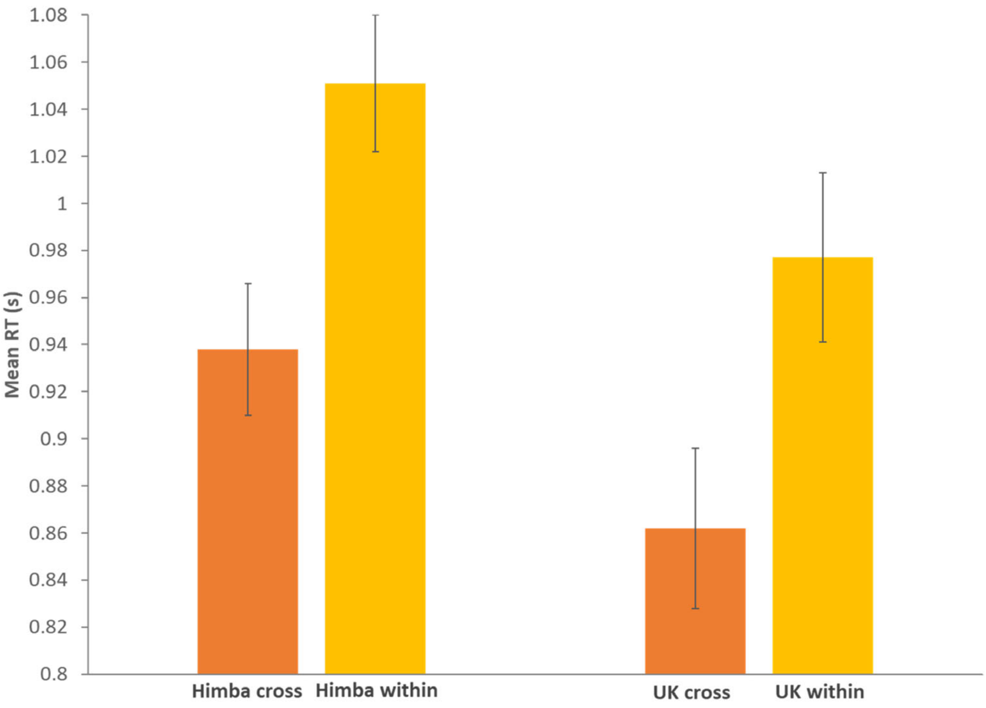


FIGURE 4 Mean RT in seconds for cross-category (orange bars) and within-category (yellow bars), error bars ±1SE for *green/blue* visual search all Himba ($N = 43$) and UK ($N = 28$) participants.

3.2 | *Serandu/burou* visual search

In this analysis, we use the label "within-category" when comparing two colors that are both labeled *serandu* or both labeled *burou* in Otjihimba. The label "cross-category" refers to comparing one color labeled *serandu* with one labeled *burou* in Otjihimba. Note however that both the cross-category (*serandu/burou*) and the within-category (*serandu* or *burou*) conditions are in fact cross-category for UK observers. A 2 × 2 × 2 ANOVA was also performed for the Otijihimba *serandu/burou* boundary. There were significant main effects of both Category (within vs. cross—as defined by Otjihimba but not English), $F(1, 83) = 81.29$, $p < 0.001$, $\eta_p{}^2 = 0.495$, and Group (Himba vs. UK), $F(1, 83) = 76.44$ $p < 0.001$, $\eta_p{}^2 = 0.479$, and these were modified by a significant interaction between Group × Category, $F(1, 83) = 19.37$, $p < 0.001$, $\eta_p{}^2 = 0.189$. Simple main effects analyses confirmed both groups of participants were faster in cross-category than in within-category conditions (Himba cross M = 0.803 s, SE = 0.021; within M = 0.850 s, SE = 0.023, $p < 0.001$ and UK cross M = 0.550 s, SE = 0.021; within M = 0.566 s, SE = 0.022, $p = 0.002$). The difference between cross-within category RTs was significantly greater for Himba participants (M = 0.471 s, SE = 0.007) than UK participants (M = 0.162 s, SE = 0.003), $t(83) = 4.40$, $p < 0.001$. The other main effects and interactions did not reach statistical significance, although the interaction between Group × Side narrowly missed statistical significance ($F(1, 83) = 3.80$, $p = 0.55$). However, the direction of that effect is in the opposite direction to those found by Gilbert et al.[29] and Drivonikou et al.[54] The UK participants RT were faster than the Himba participants RT for both sides. Only the UK participants showed a difference between left (M = 0.552 s, SE = 022 vs. right M = 0.563 s, SE = 0.22), $p = 0.052$, whereas for the Himba there was no significant difference between left (M = 0.829, SE = 0.022 vs. right M = 0.824, SE = 0.022), $p = 0.43$. All other *ps* >0.41.

Unlike for the *green/blue* task, Himba RTs were overall longer than UK participants. However, it was possible to obtain a sub-sample ($N = 9$) of Himba and ($N = 9$) UK participants with comparable RTs. In order to find this sub-sample, the average RT (across cross and within) for each participant was calculated and ordered. The fastest Himba participant's average RT was 0.57 s, the closest UK participant average was 0.565 s. Consecutive data sets from both Himba and UK participants were then selected for a range of 0.57–0.67 s for the Himba participants and 0.565–0.645 for the UK participants. The overlapping data can be seen in Figure 5.

The mixed 2 × 2 × 2 ANOVA on this smaller sample again revealed a significant main effect of Category $F(1, 16) = 14.04$, $p = 0.002$, $\eta_p{}^2 = 0.467$. The main effect of Group was not statistically significant, $p = 0.073$. There was however still a significant interaction between Group × Category $F(1, 16) = 5.29$, $p = 0.035$, $\eta_p{}^2 = 0.249$

FIGURE 5 Response time (RT) for all participants in the *serandu/burou* visual search task, The participants from the Himba and UK participants whose data overlap are shown by the filled-in circles.

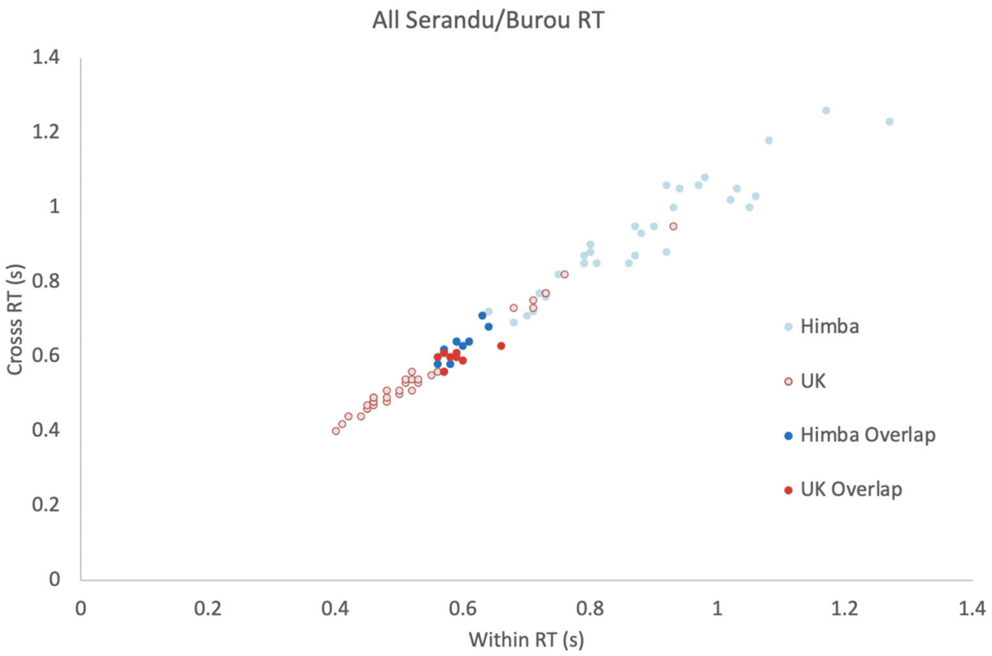
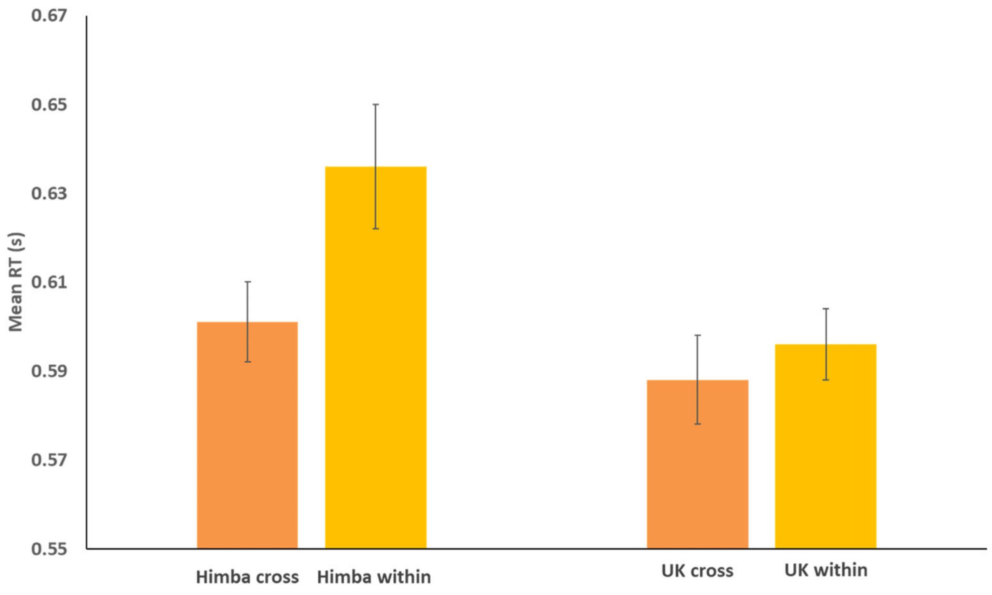


FIGURE 6 Mean RT in seconds, error bars ±1SE *serandu/burou* visual search, participants with comparable RT Himba ($N = 9$) and UK ($N = 9$). Note that both the cross-category (*serandu/burou*: Orange bars) and the within-category (*serandu* or *burou*: Yellow bars) conditions are cross-category for UK observers.



(Figure 6). All other main effects and interactions did not reach statistical significance $p > 0.071$.

Given the debate about how to deal with within-subjects effects in mixed design analysis (Howell, 2010, p. 482),[55] we conducted separate analysis of the within-subjects effects for Himba participants; this produced a significant main effect of Category $F(1, 8) = 17.45$, $p = 0.003$, $\eta_p{}^2 = 0.686$. The mean cross-category RTs ($M = 0.60$s, $SE = 0.009$) were faster than within-category, ($M = 0.636$ s, $SE = 0.014$) $p = 0.003$. However, a similar analysis for UK participants found no main effect of Category, $p = 0.325$, cross $M = 0.588$ s, $SE = 0.010$; within $M = 0.596$ s, $SE = 0.008$.

There was no difference between Himba ($M = 0.601$ s, $SE = 0.01$) and UK ($M = 0.588$ s, $SE = 0.01$) “cross-category” RTs, $p = 0.340$, but, most importantly, the Himba participants took longer to respond in the within-category condition ($M = 0.636$ s, $SE = 0.012$) than UK participants for whom this was a cross-category condition, ($M = 0.596$ s, $SE = 0.012$) $p = 0.027$ (see Figure 6).

We conducted one further analysis on our data. In many visual search tasks for colored targets, latencies are determined by other aspects of the display besides CP.[56] For example, latencies are faster to prototype colors. So, perhaps the observers learn what is the middle of the

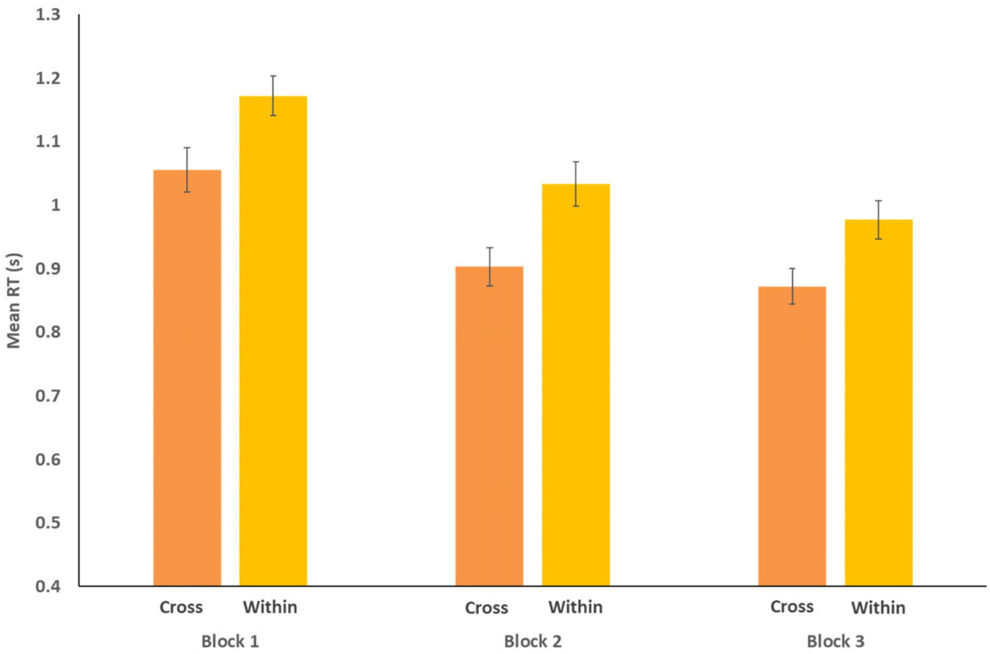


FIGURE 7 Mean latencies (cross and within) for Himba observers for the three blocks of trials in the *blue/green* visual search task.

range and this becomes some sort of prototype though, of course, that would not explain the Himba performance with the *serandu*/*burou* task. Latencies may also be faster if attention is drawn to that color and Witzel and Gegenfurtner[57] argued that CP is, in fact, found because attention is drawn to boundary colors (here the middle of the range). Both of these explanations might predict that CP would develop during the task. Hence, we examined performance in the first block of trials compared to later blocks. A 2(Block: first vs. later) × 2 (Category: within vs. cross) ANOVA was performed on the Himba green/blue data (see Figure 7). There was a main effect of Block $F(1.42, 59.46) = 59.35$, $p < 0.001$ due to observers getting faster across blocks and a main effect of Category $F(1, 42) = 183.61$, $p < 0.001$ with cross-category trials being faster. There was no statistically significant interaction $p = 0.182$.

Data storage for the data from Davidoff et al.[2] did not allow for analysis by Block but a similar analysis on the more recent UK participants gave the same outcome. As for the Himba participants, the main effect of Block $F(2, 26) = 8.71$, $p = 0.001$ and Category $F(1, 13) = 77.60$, $p < 0.001$ were statistically significant, but the interaction Block × Category was not, $p = 0.134$.

4 | DISCUSSION

CP was examined with a visual search paradigm that produced fast responses in all participants. Two color boundaries were used for both UK and Himba observers: English *green*/*blue* and the Otjihimba *serandu*/*burou* boundary. The *green/blue* boundary is present in both English and Otjihimba. CP was predicted for both populations; this turned out to be the case and with no latency differences between the populations. The *serandu*/*burou* boundary is present in Otjihimba but not in English. In English, the closest boundary colors between *serandu* and *burou* would be called *purple* and the other colors *blue*, *lilac* or *pink*. CP was predicted for all presentations because they were all cross-category for the UK population. However, for the Himba there were presentations that were within-category and these would not offer CP and so they would be slower to find the odd-one-out stimulus. Again, the predictions were fulfilled for both populations. We therefore provide evidence that, within a color category, colors look more similar than would be predicted from their perceptual distance in color space.

In giving an explanation of these findings one could look no further than the recent accounts of the top-down effects of labels (label feedback hypothesis) in color tasks.[1,58] For example, Forder and Lupyan[58] showed that it was only after hearing a color name (e.g., *green*) that observers were more accurate (showed CP) in the immediate discrimination between targets and nontargets when they spanned a color boundary (e.g., a *green* among *blues*). These top-down effects have been argued to act at early vision and some research has found category effects on the early (P1) component of the EEG trace[7,59,60] that might be interpreted as showing a change in perception. Others have found effects only at later components[61,62] but as Siuda-Krzywycka et al.[63,64] point out it is not clear that any part of the EEG trace can be observed independent of top-down effects. Could it be that changes to perception observed in our studies are just another example of the top-down effects of labels? Perhaps during the task, our observers label even covertly[65–67] the stimuli and carry those labels into subsequent trials. There is no evidence that the observers in Forder and Lupyan[58] did this but, in any case, what use is that information when any label would not be predictive of the upcoming target. Similarly, enhancement of target colors due to attention (see Reference 68) cannot be effective when the target is unknown. Anyway, feedback from labeling cannot be the only cause of CP for other populations; patients who cannot label colors nevertheless show color CP.[63,64,69–71]

Another potential explanation of our CP findings is that CP is likely to be weak or non-existent in tasks that ask for color discrimination rather than categorization provided by color terms.[4,48,49,57,72] It could be argued that our odd-one-out task[29] would necessarily prompt categorization rather than discrimination. However it is not certain why CP is found so reliably with 11 distractors but not in a design with only 3 distractors.[58] Perhaps our design allows for pop-out which is known to be affected by set size.[73] In any case, task demands that facilitate discrimination rather than categorization cannot explain the lack of CP in other suprathreshold tasks. For example, the assessment of the overall color of an ensemble of colors is not sensitive to CP,[74,75] nor is perceptual grouping (perceived orientation) of colored dots[6] and nor the division of colors that span a color boundary.[2]

It could be that finding CP depends on the stance (perceptual or categorical) of the observer.[12] Such a possibility is enhanced by the findings in Webster and Kay[6] and, importantly, by the discovery of two types (perceptual and categorical) of color sensitive networks in the brain ([76,77]; see also[78]). Thus, finding or not finding CP is like the different perceptions of the "dress" as either white and gold or blue and black.[79,80] What we have to explain, for the dress, is why observers interpret the lighting conditions differently and this is explained by Witzel et al.[81]; For color, we still have to explain why we adopt a categorical rather than a perceptual stance and admittedly that may not be easy.[22,48] Take for example, the two studies of Sun et al.[82,83] where perceptual distances were equalized in both studies. In the former study, observers were asked to track moving lines all drawn from the same color category among distractor moving lines drawn from the same and a different color category. In the latter study, the target lines were also drawn from the two categories. CP was not found in the former study, but it was in the latter but even there CP was not always present. Sun et al.[82] concluded that color categories can dynamically modulate preattention visual processing when color working memory is involved, but that attention is necessary to produce CP effects when color is irrelevant to the task. So, explanations for such subtle differences are often post hoc resorting to attention[57] and subjective evaluation.[5,14,57,84]

Regarding the Himba, Davidoff et al.[2] found that categorical similarity rather than perceptual similarity was more reliably used in implicit than in explicit categorization. Thus, for the Himba, but also for Westerners, category boundaries were overridden in the explicit task of matching-to-sample. Both populations showed a similar strong tendency to ignore color boundaries and to divide the range of colored stimuli into two equal groups. In contrast, and without recourse to attentional explanations, CP occurs so readily in implicit tasks that it would be easy to describe it as automatic. In line with this view, one notes that CP is present in a severely aphasic patient who cannot name or categorize colors.[63,71]

Roberson et al.[71] reported a series of experiments on a patient (LEW) with virtually zero color naming and color categorization ability. LEW was able to show implicit understanding of classic hallmarks of CP; for example, in experiments requiring the choice of an odd-one-out, the patient chose alternatives dictated by category rather than by perceptual distance. Thus, underlying categories appeared normal and boundaries appeared intact. Furthermore, in a two-alternative forced-choice recognition memory task, performance was worse for within-category decisions than for cross-category decisions and for LEW there cannot be a naming artifact. LEW showed that his similarity judgments for colors could be based on perceptual or categorical similarity according to task demands. His inability to make explicit use of his intact (implicit) knowledge was seen as related to his language impairment; see also Reference 85 for an account of how implicit versus explicit knowledge might differently guide visual search.

What have these studies told us about the organization of color categories? The foremost answer is that, despite the uncertainty about which tasks promote CP, a speeded odd-one-out task from 12 stimuli allows CP to be reliably shown without any concern of naming artifacts. CP was shown in the Himba for both a newly acquired category (*green*) and longer standing categories (*serandu* vs. *burou*). The origin of these within-category similarities could be based on perceptual similarities that produce similar color clusters in all languages[86] but are better explained by linguistic similarity.[40] However, despite linguistic similarity being the most likely origin of CP in the adult, the current data would seem to play down any role of language areas located in the left hemisphere. The present studies failed to find any lateralized effects but eye movements were not controlled (see Reference 72) and that will limit our conclusions given that the lateralization data are fragile.[6,14,31] Nevertheless, the same lack of lateralization is also found in stimuli that were presented so quickly as to prevent eye movements.[27,87] Indeed, given that neural networks for color categorization, unlike color naming, have been found to be represented in both halves of the brain,[78] it is a reasonable prediction that there should be no effect of side of presentation. It could be that color terms are important, perhaps essential, for laying down those bilateral categorical networks but, as shown in Roberson et al.,[71] and Siuda-Krzywicka et al.,[63,64,78] their production has become independent of language.

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CONFLICT OF INTEREST STATEMENT

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

DATA AVAILABILITY STATEMENT

The datasets generated during the current study are available online in the Open Science Framework (OSF) Repository of the Center for Open Science, https://osf.io/nkruh/?view_only=e93c3fbccaba4f638a27a778ec410bf1.

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