THESIS

COLOR MEMORY FOR OBJECTS WITH

PROTOTYPICAL COLOR MISMATCH

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ABSTRACT

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Many studies have demonstrated the effect of top-down influences on color preference and memory, but these have primarily studied short-term memory or color memory in the abstract (e.g., the experimenter names an object or substance and the subject produces a subjective match without first being exposed to a stimulus). The present study examined the effect of object color prototypicality and how such prototypicality might influence memory for colors of objects presented in non-prototypical colors (e. g., a banana presented as blue). A match between an object's prototypical and presentation colors appeared to facilitate the accuracy of matching and increase participants' confidence that they achieved a correct match; a prototypical color mismatch impaired subjects' ability to achieve a correct match. For stimuli presented in their prototypical colors, subjects tended to remember highly saturated stimuli as less saturated, and desaturated stimuli as more saturated, indicating a sort of "regression to a saturation mean". This effect did not occur for stimuli presented in a non-prototypical color or stimuli presented as simple colored circles. Evidence was not found, however, for systematic influence of object color prototypicality on the hue and/or luminance of subjects' produced matches.

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INTRODUCTION

Much research in both psychophysics and cognitive psychology has investigated the effect of top-down influences on perceptual processes. Top-down influences are cognitive processes that may affect the interpretation of a sensory stimulus. For example, something as simple as a suggestion may affect one's perception of a color, as when Loftus (1977) found that referring to a previously seen green car as blue shifted subjects' memories of the car's color toward blue. Many studies investigating the perception of color for objects with a prototypical color (i. e., objects that are usually associated with a specific color, such as bananas or leaves) have observed that subjects tend not only to remember, but to perceive the color of those objects as shifted toward the object's prototypical color (Bruner, Postman, & Rodrigues, 1951; Delk & Fillenbaum, 1965; Duncker, 1939; Hansen, Olkkonen, Walter, & Gegenfurtner, 2006; Perez-Carpinell, DeFez, Baldovi, & Soriano, 1999; Ratner & McCarthy, 1990; Ridley, 1987).

For example, Dunker (1939) exposed subjects to two cutout fabric stimuli from the same green cloth under a red illuminant[1], one stimulus cut in the shape of a leaf and the other cut in the shape of a donkey. When asked to match the color of each stimulus using a color wheel, eight of 11 subjects indicated that the leaf shape was greener than the donkey shape, demonstrating that the shape of the sample biased observers' memory of the color. Similarly, Bruner et al. (1951) cut eight shapes from achromatic (gray) paper, six of which were associated with a prototypical color (e.g., tomato: red, tangerine: orange) and two of which were neutral stimuli (oval and elongated ellipse). The experimenter named each shape when presenting it to the subject and the subject was then required to match the stimulus using a color wheel which encompassed a range of colors from yellow to red, thus including the color with which each stimulus was typically associated. Subjects initially matched each stimulus twice with the stimulus present, and then

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[1] Duncker (1939) used a red illuminant to make the green cloth appear to be a neutral color.

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attempted to match the color of each stimulus from memory either immediately, five minutes, or ten minutes after the stimulus had been removed, depending on experimental condition. For all experimental groups, matches for prototypically red objects were shifted toward red relative to the neutral gray in which they had been presented, and prototypically yellow objects were shifted toward yellow, although all stimuli had been presented in the same color. (Subjects' matches to the neutral stimuli were fairly accurate and did not exhibit as great a color shift as did the matches to the stimuli associated with a prototypical color.) Ratner and McCarthy (1990) presented subjects with several stimuli in both congruent (e. g., a red stop sign) and incongruent (e. g., a blue stop sign) colors. After viewing a stimulus and a 30-second waiting period, subjects were shown three versions of the stimulus in various colors and had to indicate which of the three most closely matched the stimulus they had viewed. Ratner and McCarthy found that subjects were more accurately able to select the correct color for the congruent color condition than the inappropriate color condition (e. g., the color of the red stop sign was remembered more accurately than the color of the blue stop sign). Thus, memory for color may be more accurate when an object is presented in a color that matches the observer's expected color for that object.

Studies have also shown that color prototypicality plays a role in color memory even when experimenters do not intend for subjects to match an object's prototypical color. Hansen et al. (2006) showed subjects digitized photographs of objects with prototypical colors and had them adjust the objects' color, or chromaticity, to appear achromatic (gray). Subjects reliably adjusted the color so that it was shifted toward the opposite of the object's prototypical color. For example, "subjects adjusted [a banana stimulus] to a slightly bluish hue—its opponent color—in order for it to appear gray" (p. 1367). Hansen et al. obtained similar findings for food

items with different prototypical colors as well (e. g., broccoli, oranges, lemons, etc.). These measurements indicate that the propensity to perceive a banana as yellow is so ingrained that the banana is still perceived as yellowish even when it is actually a neutral gray.

All of the extant literature regarding color memory has examined either memory for color after a relatively brief retention interval (i. e., the ability to accurately reproduce an object's color after a delay of no more than ten minutes), or the ability to reproduce a color entirely from memory without first being exposed to a specific experimental stimulus. For example, Bartleson (1960) presented subjects with 931 color patches. The experimenter then named an object or substance (e. g., red brick, green grass, etc.), and subjects were required to choose from among the 931 color patches the color they felt most closely resembled the named substance or object. Subjects reliably matched the named stimuli to color patches of greater saturation than the actual test stimulus (e. g., subjects indicated that green grass was greener than the chromaticity in which it was presented). Bodrogi and Tarczali (2001) performed a series of experiments to determine whether memory for color seen in context (i. e., presented as part of a photorealistic image including identifiable shape and texture) differed from memory for color presented as an isolated color patch and memory for color in the abstract (in which condition the experimenter named a familiar object and required the subject to produce a match). Their results indicated that color of prototypically colored objects was remembered to be more saturated than the actual color of the object, even after a short delay of 4 s. Bodrogi and Tarczali hypothesized that this shift in saturation occurred because in recalling the prototypical color of an object, subjects retrieved a generalized representation of that object's color rather than the actual color they perceived. These findings support Derefeldt, Swartling, Berggrund, and Bodrogi's (2004) assertion that color is represented cognitively as discrete categories, rather than as a continuum. For instance,

an observer knows that grass is green, and thus when reproducing the color of a sample of grass from memory, she will choose the best cognitive representation of the concept "green" that is available to her, regardless of the specific shade of green grass she previously viewed. If correct, these assertions suggest that memory for color may be much coarser than color vision.

The present study investigated the effect of object color prototypicality, and thus top-down influences, on long-term color memory. Clearly it has been demonstrated that cognition does have an effect on memory for color; the present experiment introduced a longer delay between encoding and test than has been previously studied in an attempt to pinpoint when the memory shift takes place and whether the shift toward prototypicality increases with time. The present study involved asking subjects to remember the color of objects presented in a different color than that with which the object is typically associated (e. g., a blue banana). A separate group of subjects saw a series of objects presented in their prototypical color, and a third group of subjects saw a series of colored circles intended to present the color in the absence of context (cf. Bodrogi & Tarczali, 2001). After stimulus presentation, subjects adjusted the color of a circle until they achieved a subjective match to the color in which the stimulus was originally presented, either immediately or after a 15-minute delay. Further distinguishing this study from prior studies, where subjects were required to choose a match from among a finite set of options, subjects were required to independently reproduce the color using a computer, and adjusted hue, saturation, and brightness of a color patch until they achieved a subjective match. The computer recorded the coordinates in *Commission Internationale de L'Eclairage* (CIE) 1931 color space (see Figure 1) of the subjective matches; these coordinates were then transformed into CIE LUV coordinates (as CIE LUV is a more uniform representation of color space; see Figure 2). The

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experimenter calculated the Euclidean distance between the coordinates of each subjective match and its respective test stimulus to establish a quantitative error score that was then compared across the conditions.

The experimenter hypothesized that subjects' subjective matches to the abnormally colored stimuli would be shifted reliably toward the objects' prototypical colors. For the prototypically colored condition, the experimenter hypothesized that subjects would remember objects' color as more saturated than the original presentation color. The experimenter further predicted that error scores for the abnormally colored stimuli would be greater than error scores for the normally colored stimuli, indicating a greater memory shift. For the context free condition, the experimenter anticipated that subjects again would remember the color of the circles as being more saturated than the original presentation, but that the error scores for the context-free condition would be greater than either of the conditions in which context was provided, as circles do not possess a prototypical color that subjects may use as a memory cue. Confirmation of these hypotheses would show that expectations regarding an object's color influence memory for that object's color, and would be consistent with the theory that colors are represented cognitively as discrete categories, which has implications for the use of color to guide visual search (Derefeldt et al., 2003). A better understanding of the cognitive processes surrounding color may lead to the development of more effective visual displays in a variety of industrial-organizational settings, such as aviation and industrial machinery.

As the computer matching task central to the proposed study has not been used previously, a pilot study was conducted to assess the feasibility of the computer matching task and to ensure that subjects would be able to accurately reproduce colors after a substantial delay.

METHOD

Participants

Participants were 21 adults who were either Colorado State University undergraduates or participants in the Research Experiences for Undergraduates program at Colorado State University[2]. We did not hypothesize that gender or age would have a significant effect on color perception or color memory, and thus did not control for these. All participants were tested with Ishihara color plates and found to have normal color vision.

Materials and Procedure

Participants saw one of two PowerPoint slideshows comprised of four colors. One slideshow contained colors to which the opponent-color mechanisms are maximally sensitive (Figure 3), and one contained four unique hues that roughly correspond to prototypical red, green, yellow, and blue (Figure 4), selected by consensus between the experimenter and the research assistant. Slides were presented on the monitor of a Macintosh iMac computer positioned 3 m from the subject. Subjects underwent 120 s of dark adaptation before viewing the slideshow, and each color was presented three times on a black background for 2 s each time; subjects saw a total of 12 slides.

After a 15-minute delay, during which subjects were free to do as they wished, participants were asked to reproduce each color five times via the computer program described previously. Participants were seated 3 m from an NES 120 AccuSync monitor and again underwent 120 s of dark adaptation. Several beeps from the computer signaled the end of the dark adaptation period, at which point a colored circle appeared on the monitor. The initial hue, saturation, and brightness of the circle were chosen randomly by the computer. Participants used

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a gamepad controller to independently adjust the hue, saturation, and brightness of the circle until they achieved a subjective match with the colors presented previously in the slideshow. After a satisfactory match was achieved, participants notified the experimenter that a match had been achieved. The experimenter then pressed the button on the controller that submitted the match to the computer, which recorded the exact chromaticity of the match. Participants matched each of the four colors five times in succession. After each match was achieved, the computer reset the hue, saturation, and brightness of the circle displayed on the monitor to randomly selected values. Prior to matching each color, participants were asked which color they were matching to ensure that all participants did in fact remember seeing four distinct colors. Participants who could not name all four colors, or did so inaccurately, had all their data excluded from data analysis.

RESULTS

Match chromaticity was recorded as CIE 1931 coordinates and was subsequently transformed into CIE LUV coordinates as the CIE LUV is the best approximation of a true color appearance space. The Euclidean distance between the match chromaticity and the actual stimulus chromaticity were calculated and represented an error score; i. e., a quantification of how accurately each match corresponded to the stimulus with which it was associated. Preliminary data analysis indicated inequality of variance between the unique hues and color opponent groups, so a non-parametric independent-samples Mann-Whitney U test was used to investigate the difference in the matching accuracy for the unique hues and color opponent slideshow by measuring which group had, overall, the greatest Euclidean distance between the test stimulus and produced match.

Figure 5 shows the results of the Mann-Whitney analysis, with error scores (labeled as "distance") indicated on the ordinate, and the frequency with which those error scores occurred indicated on the abscissa. Error scores for the unique hues condition are represented in blue on the left portion of the figures, and error scores for the color opponent condition are represented in green on the right. Participants were, on average, more accurate at producing matches to the unique hues slideshow than to the color opponent slideshow, but their responses were more variable. The error scores were, on average, significantly greater ($p < 0.05$) for the matches produced in the opponent color condition compared to the unique hues condition, suggesting that opponent-colors might have been remembered less accurately than unique hues.

DISCUSSION

The findings of the pilot study indicated that color memory has a cognitive, rather than a physiological, basis, as people were better able to remember unique hues than those that produced a strong physiological response. In addition, the experiment showed that people were able to remember colors after a delay with some accuracy, which is crucial to the current experiment.

The current experiment expands on the pilot study by introducing the concept of color prototypicality, as well as incorporating both an immediate and a delay condition.

CURRENT EXPERIMENT

METHOD

Participants

Participants were 60 Colorado State University undergraduates recruited from the Psychology Department Undergraduate Research Pool, and seven acquaintances of the experimenter added as subjects to ensure a full set of data (some participants were unable to produce matches for some stimuli, resulting in fewer matches for those stimuli). All participants were assessed for normal trichromatic color vision using Ishihara plates. Several studies have shown, rather surprisingly, that expertise (i. e., previous experience with color matching such as that obtained by art students) has no significant effect on ability to match color from memory (e. g. Bartleson, 1960; Burnham & Clark, 1955; Perez-Carpinell et al., 1999). Thus, prior experience was not considered.

Materials and Procedure

Stimuli were presented using a Macintosh iMac computer. Subjects sat at a fixed distance of 3 m from a color monitor in a darkened room and used a chin rest to stabilize the head. A fixation cross was presented in the center of a gray field (luminance 131.2 cd/m^2) for 120 s for adaptation purposes; after the 120 s elapsed, subjects viewed a series of nine objects[3] whose color was manipulated using image manipulation software (see Figure 1 for an example). Twenty-two participants saw photographs of objects which are usually associated with a specific color (e. g., pumpkin, cotton candy, traffic cone, etc.) presented on a gray background, but the color in which they were presented did not match the color with which they are usually

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[3] While nine objects seems to be a small number of stimuli, the pilot study, which utilized only four discrete colors, found that some participants were unable to remember all four colors; thus, nine, some might argue based on the pilot, may in fact be too many stimuli. Additionally, in trial runs with 12 stimuli, the experimenters themselves were unable to name all 12 from memory, and thus the task was deemed too taxing for participants.

associated (e. g., cyan pumpkin, green cotton candy, magenta traffic cone, etc.). This condition was named the incongruent color condition. Twenty-one participants saw representations of objects presented in a color congruent with their prototypical color (e. g., an orange pumpkin) presented on a gray background: the congruent color condition. The remaining 24[4] participants simply saw circles of color presented on a gray background: the context-free color condition. The experimenter determined the exact color coordinates in CIE 1931 color space (see Figure 2) for all objects using a Photo Research SpectraScan PR650 spectrophotometer, then calculated the CIE LUV coordinates based on the average of five spectrophotometer readings for each stimulus. The luminance of each stimulus was adjusted to limit luminance variation between stimuli[5], as color appearance can vary with luminance levels. The experimenter created nine distinct, randomly ordered slideshows for each condition using a Latin square; nine slideshows were necessary to ensure no stimulus appeared in the same numeric order twice to eliminate possible order effects. Each object remained on the screen for 15 s; between slides, participants saw the fixation cross again for 15 s to ensure that they continued fixating the center of the monitor.

Participants were informed that they would view a slideshow containing nine distinct colored stimuli, and their task was to remember the color of each stimulus in order to reproduce it from memory either immediately or after a short delay (the specific instruction given were appropriate to whether the participant was in the immediate or delay condition). Participants were instructed to fixate on the cross on the first slide and to remain fixated in that position, and to remember the color of the stimuli as best they could. They were also told they did not need to

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[4] The differing numbers of participants per condition occurred in an attempt to obtain at least 20 usable data points for each stimulus. Some participants produced matches to one or more stimuli that were unusable, either because the participant indicated s/he had accidentally pressed "submit" before achieving a satisfactory match, because the participant could not remember the stimulus at all, or because the ColorMatch program had frozen and the participant could not finish the procedure.
[5] Luminance values ranged from 22.54 – 25.84 cd/m^2.

remember the specific order in which the stimuli were presented, only the color of each stimulus. During the next phase, in which the participant reproduced the colors from memory (described below), participants were instructed to be as accurate as possible in recreating the color of each stimulus.

After viewing the slideshow, 32 subjects (10 for the congruent condition, 11 each for the incongruent and context-free conditions)[6] were asked to produce matches to the stimuli immediately. The remaining 35 subjects (11 each for the congruent and incongruent conditions, 13 for the context-free condition) were asked to return after 15 minutes to complete the matching task. During the matching procedure, subjects sat 3 m from a NES 120 AccuSync monitor in a darkened room and used a chin rest for head stabilization as they did in the pilot study. After a period of adaptation to a gray background of 120 s, a colored circle appeared on the monitor; as in the pilot study, the initial color of the circle was chosen randomly by the computer. Participants indicated to the experimenter which stimulus they were currently attempting to match (e. g., "I will match the tiger now"); if a participant did not name the stimulus before attempting a match, s/he was prompted by the experimenter. Participants used the joystick of a gamepad to adjust the hue, saturation, and brightness of the circle until they achieved a subjective match to the color in which the object was presented during the first phase of the experiment (subjects were given a practice session with the joystick prior to viewing the slideshow to ensure they were comfortable with the equipment). The participant indicated the achievement of a subjective match by pressing a button on the game pad, at which point the computer recorded the chromaticity coordinates of the match specified by the participant. Participants produced a match to each stimulus color three times in a row; i. e., the subject matched stimulus 1 three times, then stimulus 2 three times, and so on. Additionally, after the

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[6] See footnote 4.

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participant produced each match, the experimenter asked him or her to indicate his or her confidence that s/he was able to accurately match each color using a scale of 0 to 100, where 0 indicated the subject had 0% confidence that s/he had matched the color accurately, and 100 indicated the subject had 100% confidence that s/he had matched the color accurately. For each produced match, the experimenter manually recorded participants' self-ratings of confidence using pen and paper.

RESULTS

All chromaticities were expressed in CIE LUV coordinates, as the CIE LUV color space has been offered as a perceptually uniform color space. The vector length (Euclidean distance) between the physical and matched chromaticity was taken as representing the accuracy of the matches. In addition, all chromaticities were graphed; these graphs were then superimposed onto CIE LUV color space to yield a graphical representation of the distribution of the points in color space. Data were analyzed quantitatively using multiple linear regression, investigating the effect of slideshow type, delay condition, and interaction between slideshow type and delay condition on vector length and confidence rating. The context-free condition was used as the control condition for analysis purposes.[7]

The graphical representation of the matches' position in CIE LUV color space was also used to determine whether the discrepancy between the matches and original stimulus color occurred in any consistent pattern. In general, for the congruent condition, matches were shifted toward a desaturated version of the prototypical color (see Figures 6-14); this occurred for all stimuli with highly saturated colors (e. g., traffic cones, strawberries, pumpkin). Desaturated stimuli in the congruent condition (e. g., tiger, chicks, cotton candy) tended to be remembered as more saturated.

Matches for the incongruent condition consistently showed much more variability than matches for the congruent condition and were often distributed widely around the available color

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[7] Data analysis was run twice: once with all data points included, and once with outliers removed from the analysis using the graphical representation of all matches' positions in CIE LUV color space. An outlier was defined as any match that was clearly in an opponent-color category from the original stimulus (e. g., a match produced for the green congruent frog stimulus that fell in the red area of CIE LUV color space). Although the regression coefficients changed slightly after the removal of the outliers, the basic relationship between the experimental conditions remained the same (e. g., analysis of vector length both including and excluding outliers indicated vector length was longest for the incongruent condition and shortest for the congruent condition). Additionally, all relationships that were significant when outliers were included remained significant when outliers were excluded; likewise for nonsignificant relationships. This indicates that removal of the outliers did not significantly affect the outcome of the experiment. The analysis reported here was done on the full dataset with outliers included.

space (see Figures 15-23). As a result, it is difficult to interpret whether there had been any systematic shift for stimuli in the incongruent condition. A similar issue occurred with the context-free stimuli (see Figure 24-32). It is possible that because participants were no longer able to rely on the shape of each stimulus to provide a cue to its color, there was less agreement among participants as to what the "correct" color was for stimuli in the incongruent and context-free conditions.

Vector length for the context-free slideshow condition differed significantly from zero (M = .310, t = 20.952, p = .000; see Table 1), indicating that subjects' matches differed significantly from the original stimuli. Although there were no significant differences in vector length between the context-free and congruent (p = .700) or context-free and incongruent (p = .237) conditions, average vector length was shortest, and thus accuracy was greatest, for the congruent slideshow condition (M = .302). Accuracy was poorest for the incongruent slideshow condition (M = .335), indicating that participants showed greater error when producing matches to incongruent stimuli than to congruent or context-free stimuli, though this did not achieve statistical significance. The presence or absence of the delay did not significantly affect vector length (p = .615), nor was there a significant interaction between slideshow type and delay condition.

Confidence ratings differed significantly from zero for the context-free condition (M = 52.906, t = 24.321, p = .000; see Table 2), indicating that, on average, participants were fairly confident in the accuracy of their matches. Confidence also differed significantly for the context-free and congruent conditions (t = 5.122, p = .000), indicating participants were significantly more confident when producing matches to the congruent stimuli (M = 69.052) compared to the context-free stimuli, and the context-free and incongruent conditions (t = 4.459,

p = .000), indicating participants were significantly more confident when producing matches to the incongruent stimuli (*M* = 66.623) compared to the context-free stimuli. Confidence ratings were highest for the congruent condition and lowest for the context-free condition. There was also a significant interaction between slideshow type and delay condition, with confidence ratings for the incongruent slideshow delay condition (*M* = 56.373) significantly lower than those for the incongruent slideshow with no delay (*t* = -2.380, *p* = .018). This interaction suggests that, for the incongruent condition, participants who produced matches after the 15-minute delay were significantly less confident in their matches than those in the incongruent condition who produced matches immediately. There were no significant differences between the delay and immediate conditions for the congruent or context-free slideshows (*p* = .093 and .438, respectively). As expected based on a large body of previous research indicating that there is no consistent relationship between confidence and accuracy (e. g., Kassin, 1985; Willingham, 1958) for a variety of tasks, there was no significant correlation between confidence and vector length (*r* = -.041, *p* = .318), despite participants' apparent beliefs.

GENERAL DISCUSSION

Hypotheses relating to systematic shifting of produced matches relative to the original stimuli were generally not upheld. For the prototypically colored condition, it was hypothesized that subjects would remember objects as more saturated than the original stimulus; on the contrary, the change in saturation of matches relative to the original stimulus appears to depend on the saturation of the original stimulus, as highly saturated stimuli were remembered to be less saturated than the original stimulus, and desaturated stimuli were remembered as more saturated than the original. Additionally, the results did not support the hypothesis that subjects' subjective matches to the incongruent stimuli would be shifted reliably toward the objects' prototypical colors; greater variability in match coordinates for the incongruent condition indicated that no systematic shift occurred for the incongruent stimuli. Neither do the data support the prediction that accuracy would be worse for the incongruent vs. congruent condition, as although match errors were greater for the incongruent than the congruent condition, this did not achieve statistical significance. The hypothesis regarding the context-free condition was also not upheld: due to the degree of variability for produced matches it was not possible to determine whether participants experienced a systematic shift in saturation, and although the vector length was greater for the context free condition than the congruent condition, it was not significantly so.

Although the results were not statistically significant, in general participants produced the most accurate matches for the congruent condition. Interestingly, match errors (vector lengths) were greater for the incongruent condition than the context-free condition. This may possibly indicate that participants had more difficulty accurately reproducing stimuli that had contextual information but whose color did not match their prototypical color than they did accurately

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reproducing stimuli with neither contextual information nor prototypical color. It is possible that a mismatch between participants' prior expectations of an object's color and that object's actual color may be more detrimental to their ability to remember that color than a complete lack of contextual information. That is, the contextual cues in the incongruent condition may actually make accurately reproducing the objects' colors more difficult. As the differences between slideshows were not significant, however, this is merely speculative.

The fact that highly saturated stimuli were remembered as less saturated than their original presentation color, whereas desaturated stimuli were remembered as more saturated than their original presentation color, may be partially explained by the previously discussed propensity of observers to recall prototypical colors based on the color category to which that prototypical color belongs rather than memorizing the actual color of a specific object. For example, observers, in attempting to recall the color of a specific pumpkin, will use the cognitive representation of pumpkins as generally orange rather than attempting to reproduce the particular color of the pumpkin with which they were presented (Amano, Uchikawa, & Kuriki, 2002; Bodrogi & Tarczali, 2001; Derefeldt et al., 2004; Ridley, 1987). It is possible that participants' cognitive representations of prototypically colored stimuli somehow "average out" saturation; that is, the cognitive representation of the degree of saturation of an object tends to regress toward a mean degree of saturation. This would explain why highly saturated stimuli were remembered as less saturated while desaturated stimuli were remembered as more saturated. This is consistent with Derefeldt et al.'s (2003) proposed term "cognitive color," which they define as the classification of a color, following the initial visual processing of that color, into a single semantic color category. Derefeldt et al. differentiate cognitive color space from perceptual color space in that the definition of a perceptual color space has its basis in the actual

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physical attributes of a color, whereas "cognitive color space would refer to the internal categorical representations of the color including color names" (p. 8). It is conceivable that saturation has less influence than hue on cognitive color representations, thus resulting in participants primarily recalling the hue of a stimulus and not the saturation when producing a match. That this shift in saturation did not occur for the context-free and incongruent conditions may simply reflect participants' poorer ability to accurately remember any aspect of those stimuli.

Amano et al.'s (2002) findings also support this theory of categorical color processing. They found that it was more difficult for observers to detect color changes in stimuli (i. e., indicate a previously seen picture as "new" when its color had been altered) when those changes were limited to the same color category as the initial stimulus presentation, and assert that this may indicate the presence of multiple mechanisms responsible for color processing in visual memory. Although Amano et al. did not specifically investigate saturation, it is possible that there is a separate "saturation" mechanism upon which people rely less than hue when attempting to recall colors. A replication of Amano et al.'s experiment focusing on saturation rather than hue—i. e., how great of a decrease/increase in saturation is required for observers to recognize a color as "new"—would shed some light on this subject.

Clapp, Kirk, and Hausmann (2007) suggest that there may be a difference in the way perceptual color and cognitive colors are processed: visual color processing appears to be processed mainly by the right hemisphere, whereas color naming is primarily processed by the left hemisphere (although this may simply be due to the verbal nature of color naming). Derefeldt et al. (2003) themselves assert that there may be a neurological basis for the cognitive categorization of color, citing patients who suffer damage to the occipito-parietal cortex lose the

ability to categorize colors. The modular characteristic of neural processing of color is further supported by the case study of patient QP performed by Jakobson, Pearson, and Robertson (2008): after an accident resulting in damage to QP's occipital lobe, she selectively lost the ability to remember colors, although she performed normally on tasks of color discrimination, naming, and knowledge. This seems to support Derefeldt et al.'s (2003) assertion that different aspects of vision are processed and represented in discrete neural areas. A replication of the present study, with care taken to eliminate some limitations (see section below) and altered to include color discrimination and naming tasks, done in an fMRI could help determine whether or not this neurological basis is detectable in healthy observers and possibly pinpoint the area in the occipital lobe responsible for color categorization.

While color memory may seem a relatively minor detail to those outside the field of color science, Hansen et al. (2006) assert that in fact cognitive influences on perceptual processes play a major role in the ability of the human visual system to achieve color constancy. That is, Hansen et al. suggest that observers combine preconceived notions about the color of objects with contextual information to determine color appearance regardless of the light source, thus allowing observers to "factor out" any chromatic contribution of the light source based on prior knowledge of an object's color. Without this ability to "factor out" the chromaticity of the light source, the same object would appear to change color as the dominant wavelength of the illuminant changed, which would be disorienting to say the least. On a more practical level, cognitive color space is also necessary for the use of color to guide visual attention to the part of a display where it is needed (Derefeldt et al., 2003), as one must have a basic cognitive

representation of the color for which they are searching. A more thorough understanding of how color is represented cognitively has far-reaching implications in an industrial-organizational setting, as well as advancing the state of the field of visual science in general.

The present measurements appear to lead to different conclusions than some previous research. For example, Siple and Springer (1983) suggest that memory for object color is processed independently rather than being integrated into a representation of a specific example of that object. They based this conclusion on their experimental findings that subjects' memory for colors of fruits and vegetables was no more accurate when subjects saw photographs of objects than it was when subjects saw colored silhouettes of the same objects with no texture information, color patches possessing the texture of the objects but not the shape, or color patches sampled from the photographed objects but having no texture cues. Thus Siple and Springer propose that memory for color does not appear to be enhanced by placing color in a context. Our finding that there was far less variability for the congruent relative to the incongruent and context-free conditions appears to suggest otherwise (as do our nonsignificant vector length results). This difference could be due to the difference in our experimental designs, as the current study did not include a silhouette condition, and not every congruent and incongruent stimulus color was represented in the context-free condition. Similarly, Ridley (1987) performed a study designed to determine whether cognitive representations of objects with prototypical color were based primarily on the observer's actual prior experience of the color of a typical member of that category of objects or a more saturated version of the color label usually applied to that class of objects. That is, when matching the color of a tomato from memory, would observers choose a color close to that of an actual tomato—a red-orange—or one that more closely resembles the primary color red? Ridley reported that subjects reliably

remembered a tomato-shaped stimulus as a more saturated red than a circular stimulus presented in the same color, although in reality tomatoes are seldom a primary red. Ridley interpreted this to mean that subjects remembered the color of a tomato as belonging to the category "red", in keeping with the prospect of discrete cognitive color categories. However, given that participants did not indicate the tomato-shaped stimulus was a red-orange, Ridley concluded that they were not relying on a cognitive representation of the specific object in question (i. e., an object belonging to the category "tomato"). It is unclear why the present experiment did not find a similar shift toward a more saturated, primary version of the original stimuli, although it may be because the current experiment did not contain many prototypically colored stimuli that fell into "intermediate" color categories (e. g., red-orange, blue-green, etc.). The limitations discussed below also likely have some influence in this regard. Ridley also did not specifically focus on saturation differences in color memory for highly saturated vs. desaturated stimuli but rather on saturation and hue combined; thus it is unclear whether his findings support a "regression to the saturation mean" as those of the current study appear to.

That the presence or absence of a delay prior to producing matches did not significantly affect participants' accuracy is highly counterintuitive, particularly considering the existence of research indicating that delays far shorter than the one used in the current experiment (up to 10 s) negatively impact color memory performance in both pigeons (Farthing, Wagner, Gilmour, & Waxman, 1977) and humans (Francis & Irwin, 1998). In the current experiment, participants saw the slideshow in one room, and then had to enter another room in order to begin the matching process. The time required for the move was not recorded, but was likely greater than 10 seconds. Francis and Irwin (1998) found that a 10 second delay decreased the accuracy of their participants' memory for color, so it is possible that even the short delay due to the move

degraded the memory of participants in the immediate condition enough to render their performance indistinguishable from those in the delay condition. Additionally, prior to beginning the matching task, all participants dark-adapted for 120 s, a delay which, again, may have been sufficient to affect the memory of the participants in the immediate condition. In the future it may be advantageous to have the immediate condition be truly immediate; that is, to have the participants see a stimulus and match it immediately, before moving on to the next stimulus, rather than showing them all the stimuli and then having them begin the matching task. The current study was unable to enact this paradigm due to equipment constraints: the ColorMatch program could not be run concurrently with the slideshow, so it was necessary for participants to finish viewing the slideshow before moving to the matching task.

Limitations

Unfortunately, this study encountered some significant issues that limit the generalizability of the findings and could be addressed in future studies. It was clear during the data collection process that some participants put far more effort into reproducing the colors than others: some took a great deal of time and carefully adjusted both color and brightness; others painstakingly adjusted color, but not luminance; and some participants sped through the matching process. This variability in the effort exerted by different participants makes it difficult to determine the true reason for differences in accuracy between the conditions. While it is difficult to completely control for individual differences in participants' motivation, perhaps motivational differences could be minimized by recruiting strategies aimed at people with an interest in color science research, rather than simply using undergraduate students who are required to participate in research projects for credit as part of their degree program.

Additionally, there was a clear difference in the ease with which participants wielded the controller used to produce the match. An informal survey of participants revealed that participants who self-reported experience with video gaming systems seemed able to produce matches quickly, more accurately, and with fewer accidental submissions (i. e., a match submitted accidentally before the participant was satisfied with it) than those who reported they did not play video games regularly. As formal data were not collected, it is unclear to what extent prior experience with video game controllers affected the accuracy of participants' matches. Nonetheless, it would be beneficial if all participants were given more of an opportunity to practice with the controller and matching procedure before data collection, as the brief practice session allowed in the current experiment may have been insufficient for some participants. Ideally, participants would be selected in advance and asked to complete a number of practice sessions in order to thoroughly familiarize them with the procedure; unfortunately, this was not feasible in the current experiment due to a lack of resources.

Another major issue was the fact that due to the nature of the ColorMatch program, all matches were produced against a black background, whereas in the slideshows stimuli appeared on a neutral gray background. The difference in luminance between the backgrounds likely affected observers' ability to accurately match the colors: the lower luminance of the ColorMatch background caused colors to appear brighter on the CRT monitor than in the slideshow presentation. As luminance is factored in when calculating CIE LUV coordinates from CIE 1931 coordinates, it is possible that this luminance difference did influence the hue of the matches. In the future, isolating the stimulus objects and presenting them on a gray background identical in luminance would be an uncomplicated way to solve this issue.

Also affecting the interpretability of the results was the finding during data analysis that the coordinates of some of the participants' matches appear to have been recorded unreliably for reasons that are unclear. For example, when graphing matches produced for the congruent frog stimulus, which is green, in CIE LUV color space, the coordinates of some matches fell in the red area of color space, despite the fact that none of these matches appeared perceptually red to this particular experimenter while participants were producing them (although it is worth noting that there were two experimenters and so it is possible that some of the produced matches observed by the other experimenter were indeed perceptually red). This experimenter ran the experiment herself to determine the cause of this discrepancy, and found that ColorMatch had indeed recorded the coordinates of the congruent frog match as red, despite the fact that the actual color produced was perceptually a saturated green. As discussed in footnote 7, in an attempt to correct for this, produced matches falling in an opponent color area from the original stimulus chromaticity were designated as outliers, and data analysis was run twice: once including the aberrant matches, and once after they had been eliminated. As previously noted, the elimination of the outliers did not significantly affect the relationships between the variables. It is unknown whether the outliers were due to an issue with data recording on the part of the ColorMatch program, or whether participants were in fact incorrectly remembering the stimulus chromaticities. Because the recording accuracy of the matches varied from individual instance to instance rather than degrading steadily over time, this does not appear to be an issue with equipment decalibration; as such, it is very difficult to determine a cause for the aberrant matches, and due to the lack of a clear reason for the outliers, they were retained during data analysis.

SUMMARY AND CONCLUSIONS

For the congruent slideshow condition, participants exhibited a tendency to remember highly saturated stimuli as less saturated than the original presentation color, and desaturated stimuli as more saturated than the original presentation color. This "regression to the saturation mean" may indicate that participants are relying upon a cognitive representation of the general color category to which each object's prototypical color belongs, rather than attempting to match the specific color of the stimulus they saw. There was no systematic shift in saturation for the incongruent or context-free conditions.

Participants were far more confident when producing matches for the congruent condition than for the incongruent and context-free conditions, despite the fact that overall accuracy was fairly poor for all experimental conditions. Confidence was lowest for the incongruent condition, indicating that participants felt they had a more difficult time producing matches in the absence of contextual information. There was no relationship between confidence and accuracy.

Participants' accuracy did not appear affected by the presence or absence of a 15-minute delay. As previous research has shown that delays of a matter of seconds can affect the accuracy of color memory, it is possible that the immediate condition in the current experiment was not immediate enough, as participants had to be moved to another room and undergo 120 s of dark adaptation prior to beginning the matching task. The interval required for these procedures may have been sufficient to degrade the performance of participants in the immediate condition enough to cause it to be indistinguishable from that of the participants in the delay condition.
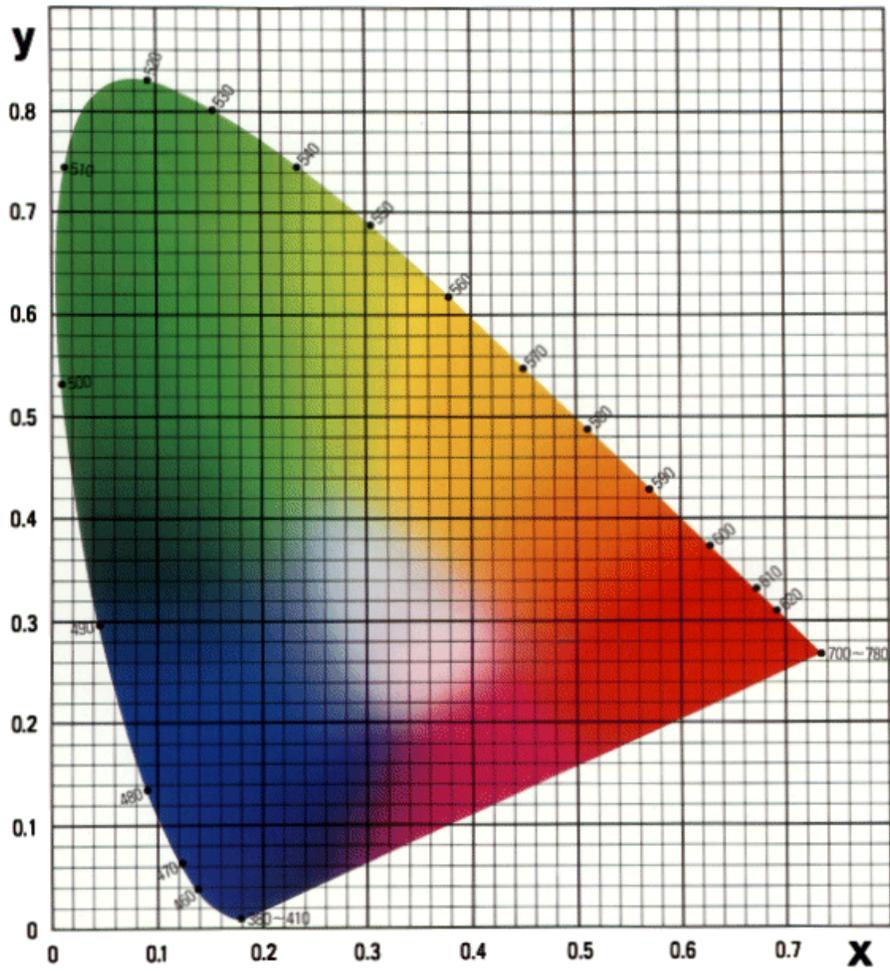
Figure 1. Diagram of CIE 1931 color space. Wavelengths of light are represented by values on the border of the polygon. Any existing color may be represented by coordinates (X, Y) in the plane. In the current experiment, the computer recorded the CIE coordinates of the color participants indicated as a match to the actual color of the stimulus.
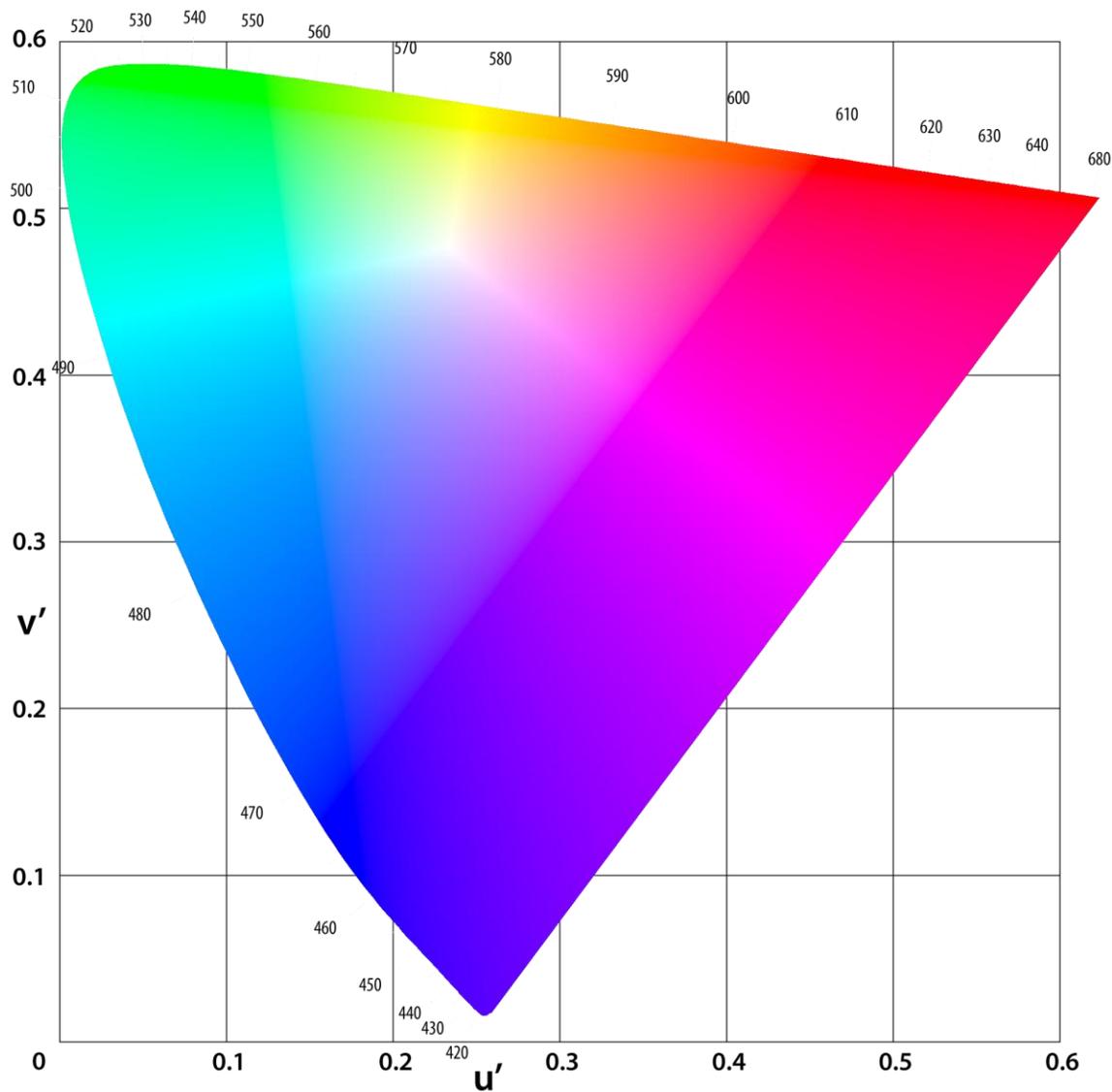
Figure 2. Diagram of CIE LUV color space. In the proposed experiment, the distance between the coordinates of the match and the coordinates of the presentation color were calculated to determine the magnitude and direction of the shift between remembered color and presentation color. For example, one might predict subjects' matches to a banana presented in a color corresponding to (0.2, 0.2) would be shifted toward the yellow region of the color space (i. e., upward and to the right).
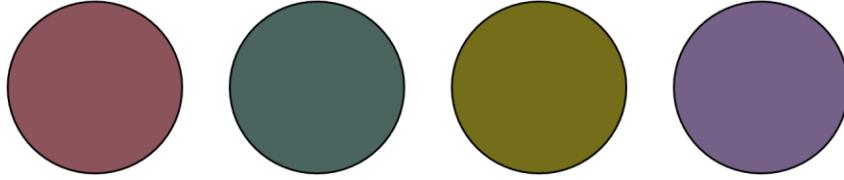
Figure 3. Colors to which opponent-color mechanisms are maximally sensitive as presented in the pilot study slideshow.
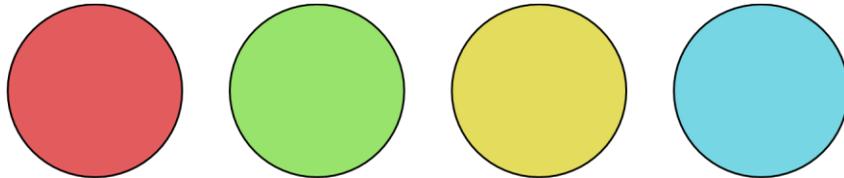
Figure 4. Unique hues presented in the pilot study slideshow.
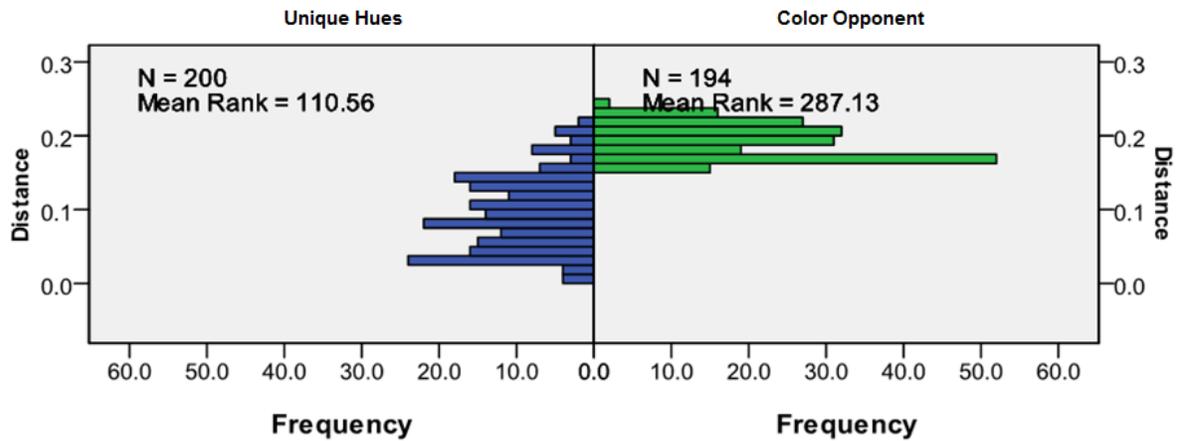
Figure 5. Graph showing the Mann-Whitney U test results for the pilot study. Matches were more accurate but more highly variable for the unique hues condition, showing that while participants were more effective at matching the unique hues slideshow, there was more variability among the matches they produced.

Congruent
Frog
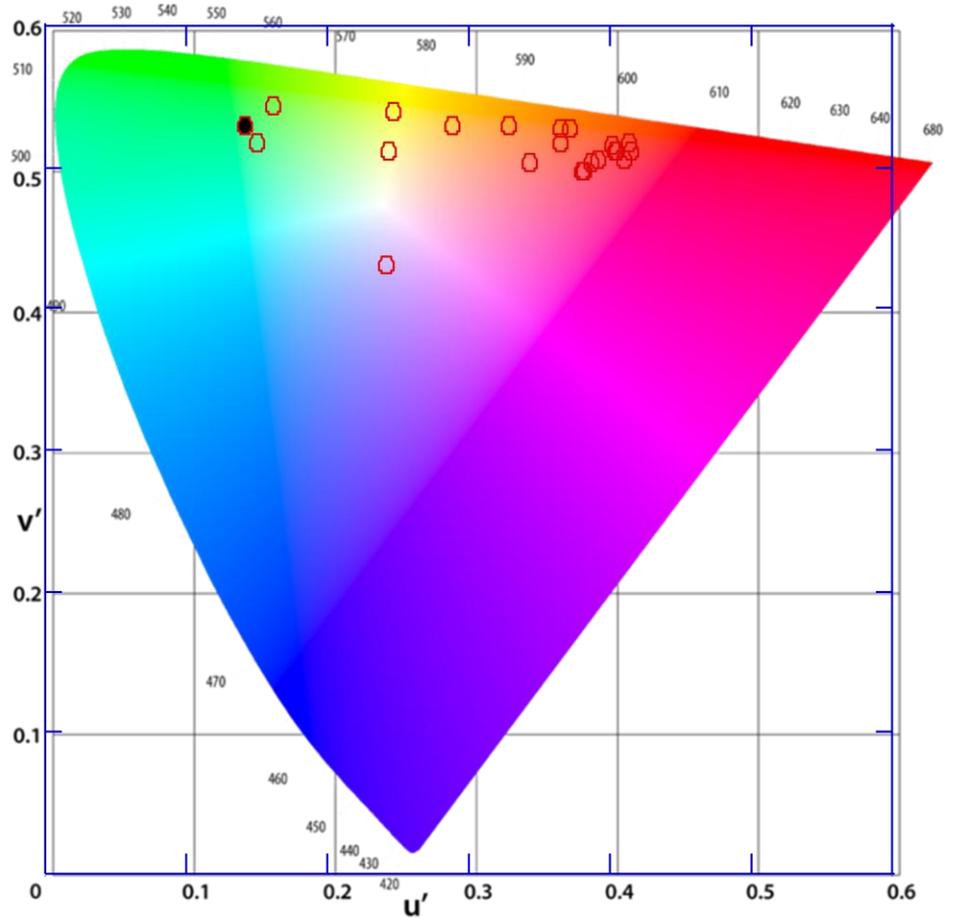
Figure 6. Matches produced to the congruent frog stimulus graphed in CIE LUV color space. The original stimulus chromaticity is indicated by the black dot.
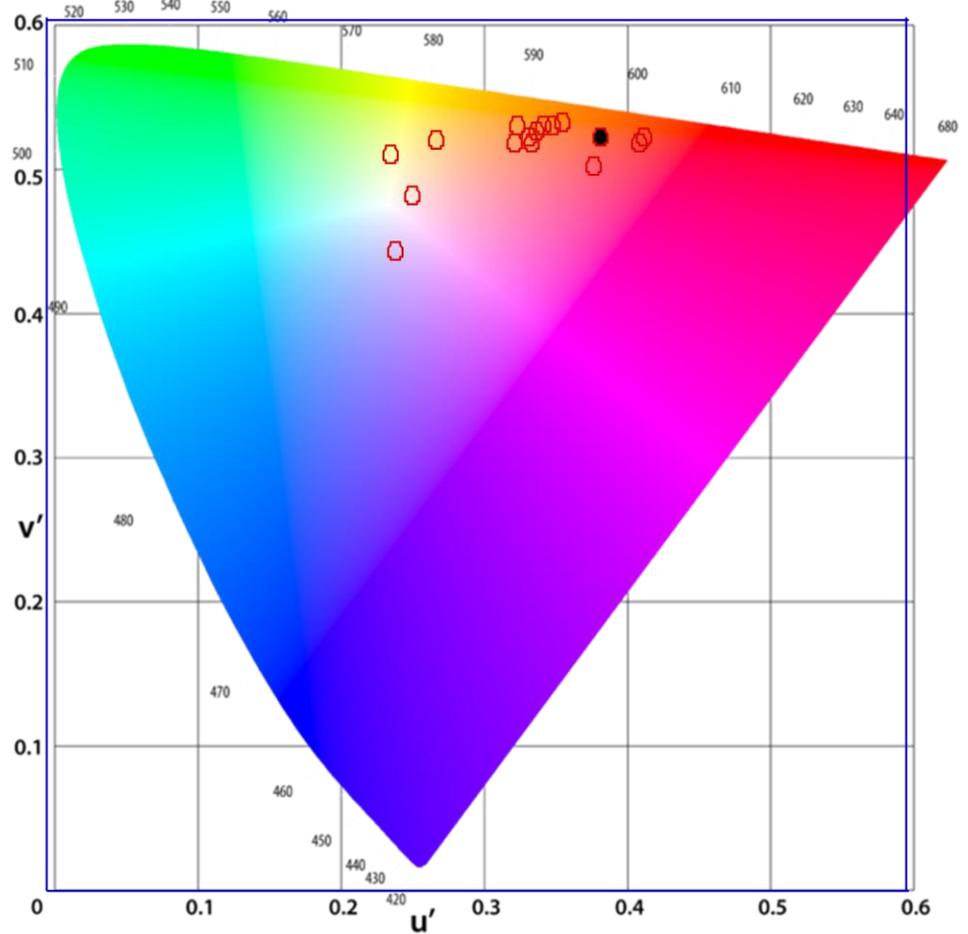
Figure 7. Matches produced to the congruent strawberries stimulus graphed in CIE LUV color space. The majority of participants produced matches less saturated than the original stimulus (represented by the black dot).
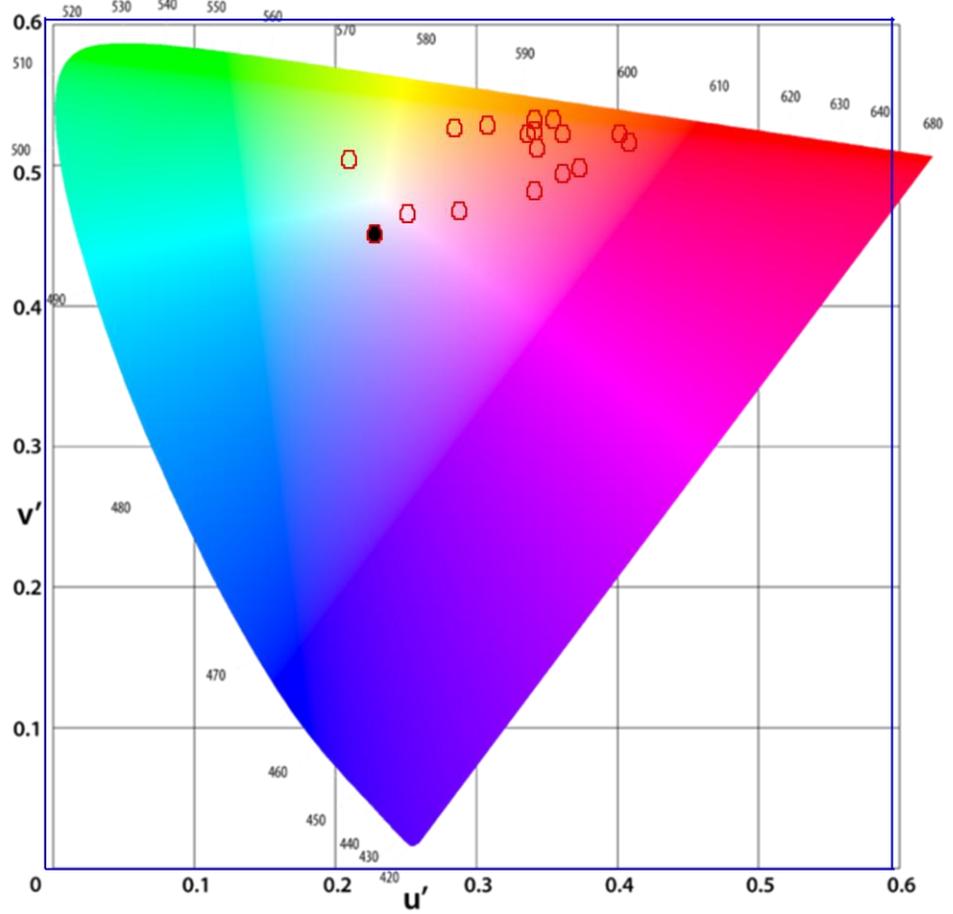
Figure 8. Matches produced to the congruent cotton candy stimulus graphed in CIE LUV color space. The majority of participants produced matches that were more saturated than the original stimulus (represented by the black dot).
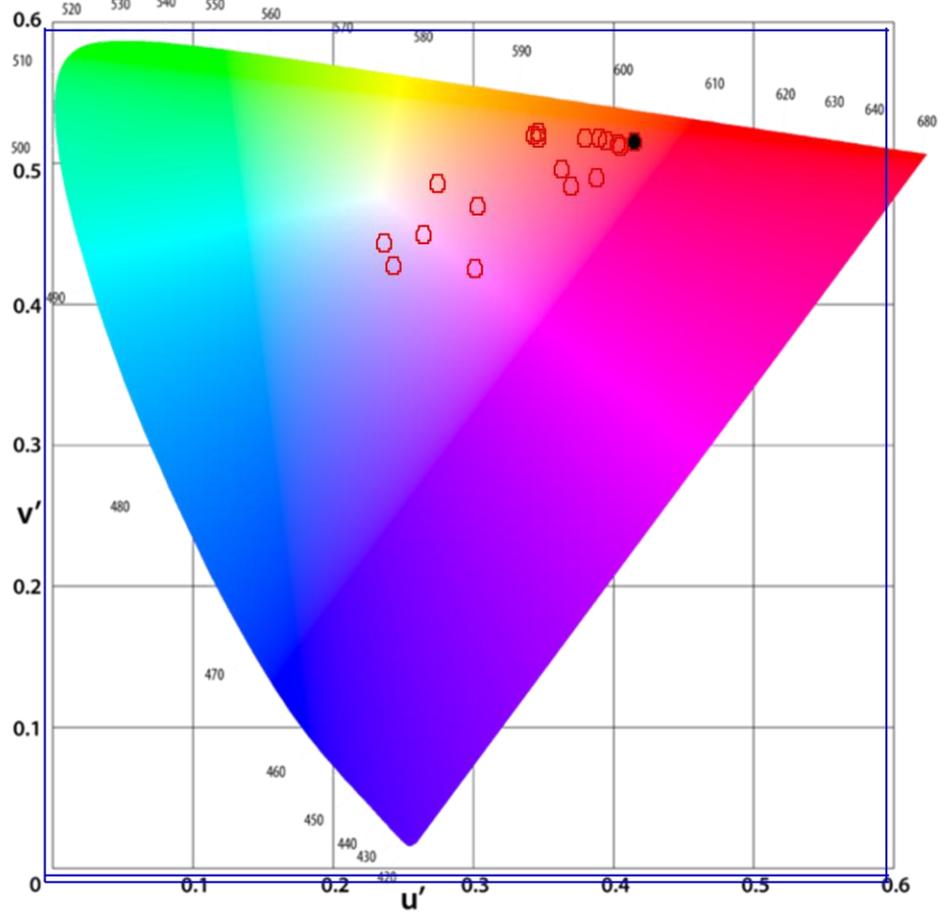
Figure 9. Matches produced to the congruent rose stimulus graphed in CIE LUV color space. The majority of participants produced matches that were less saturated than the original stimulus (represented by the black dot).
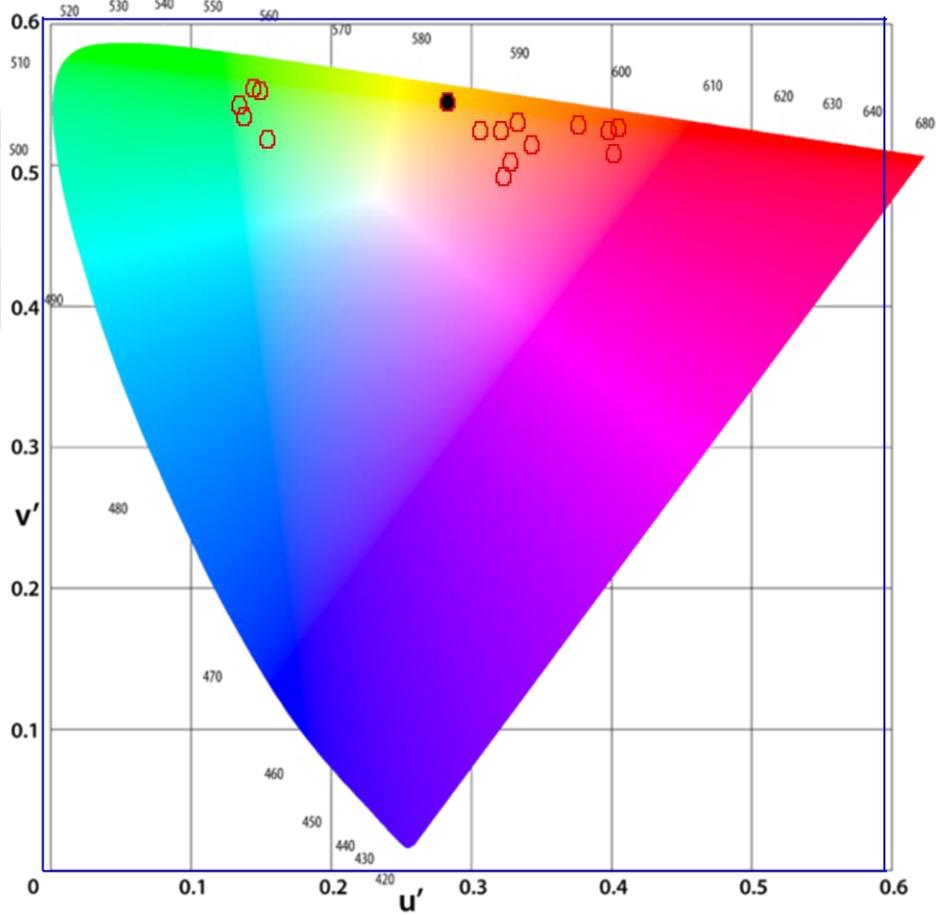
Figure 10. Matches produced to the congruent chicks stimulus graphed in CIE LUV color space. The majority of participants produced matches that were more saturated than the original stimulus (represented by the black dot).
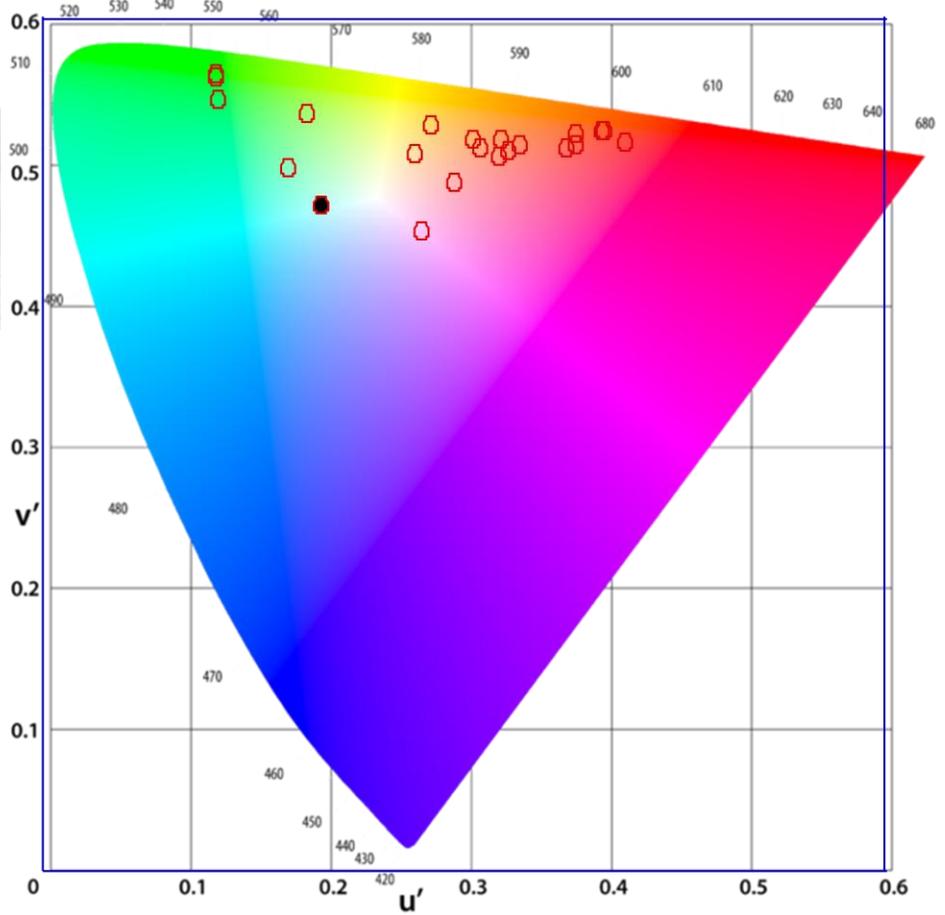
Figure 11. Matches produced to the congruent leaves stimulus graphed in CIE LUV color space. Original stimulus chromaticity is represented by the black dot.
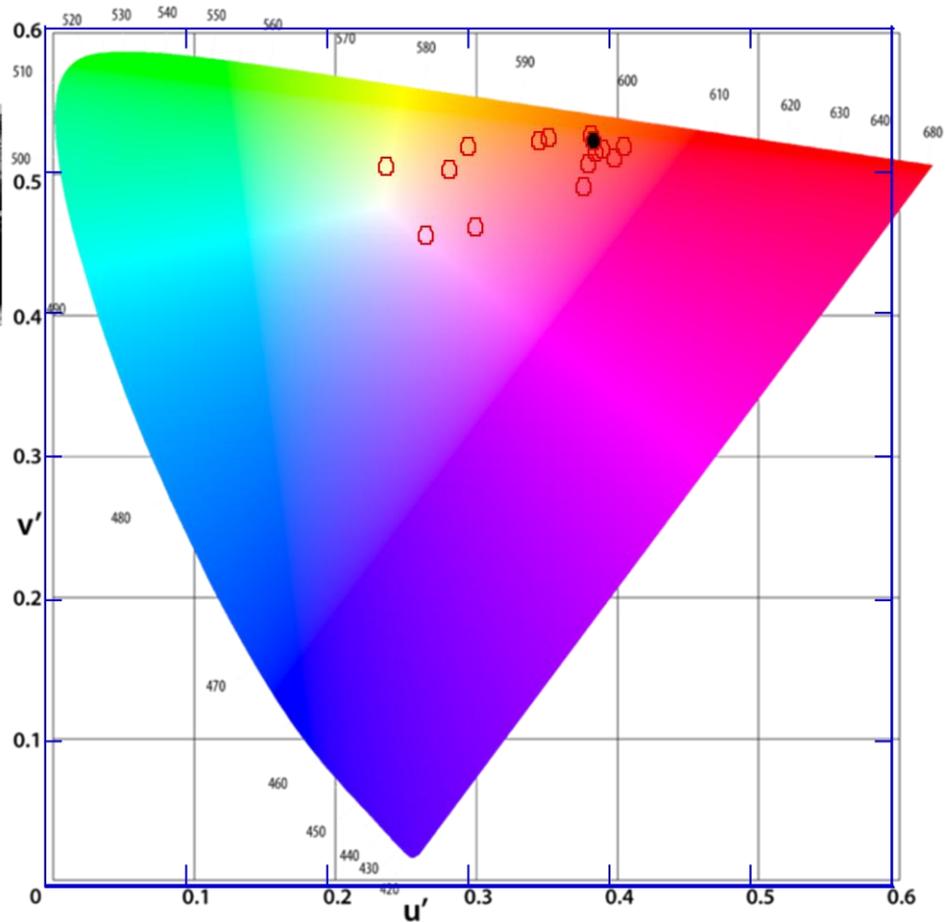
Figure 12. Matches produced to the congruent cones stimulus graphed in CIE LUV color space. The majority of participants produced matches that were less saturated than the original stimulus (represented by the black dot).
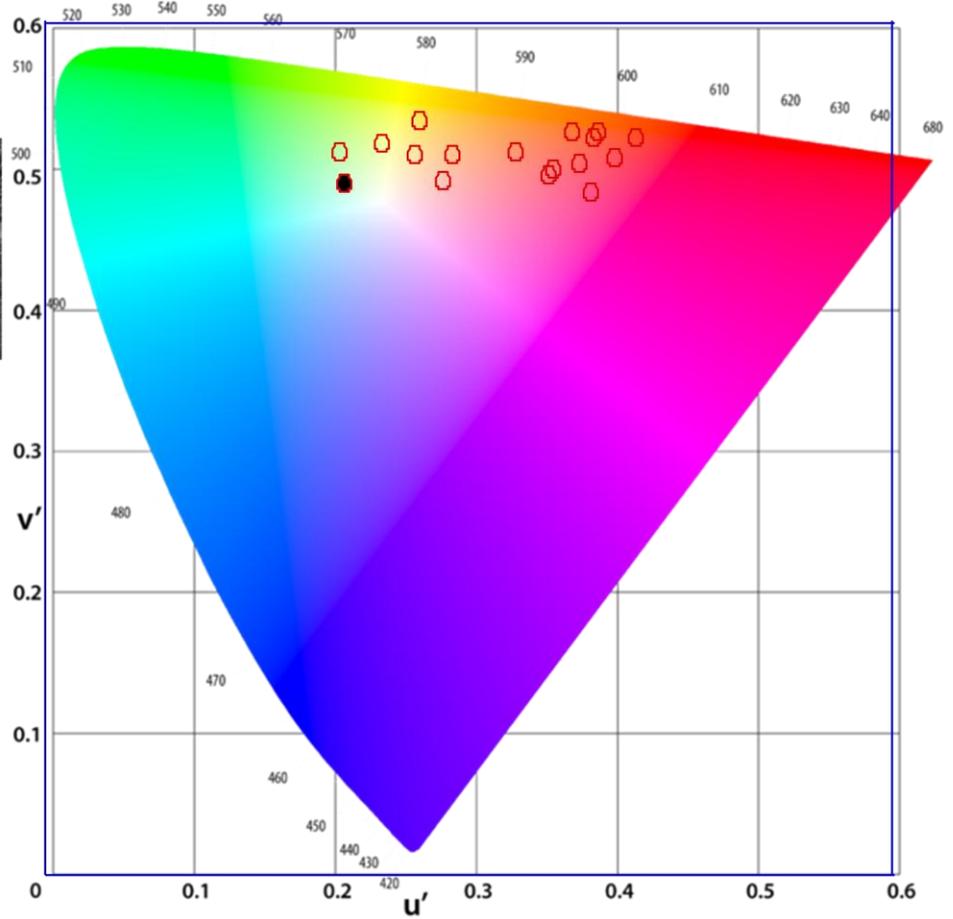
Figure 13. Matches produced to the congruent tiger stimulus graphed in CIE LUV color space. The majority of participants produced matches that were more saturated than the original stimulus (represented by the black dot).
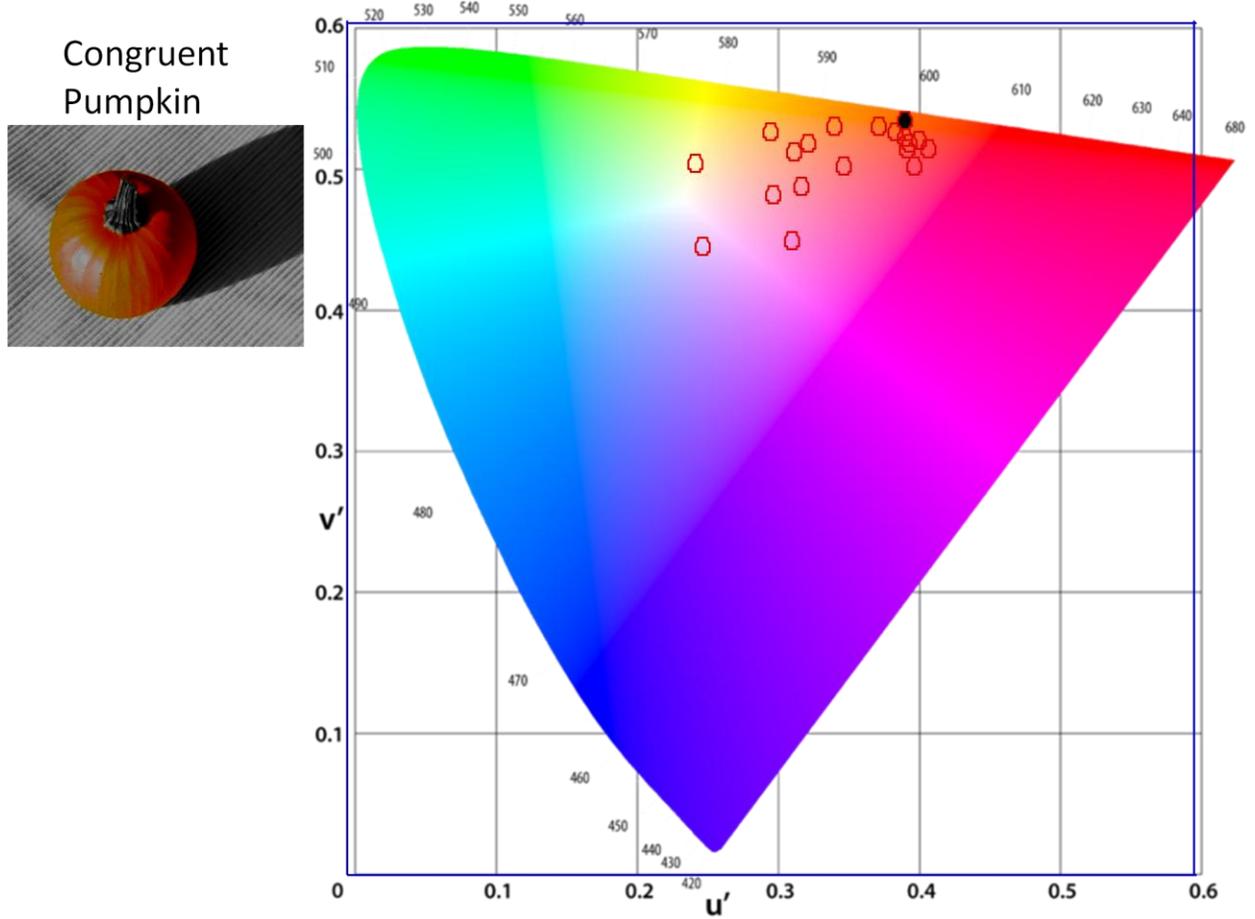
Figure 14. Matches produced to the congruent pumpkin stimulus graphed in CIE LUV color space. The majority of participants produced matches that were less saturated than the original stimulus (represented by the black dot).
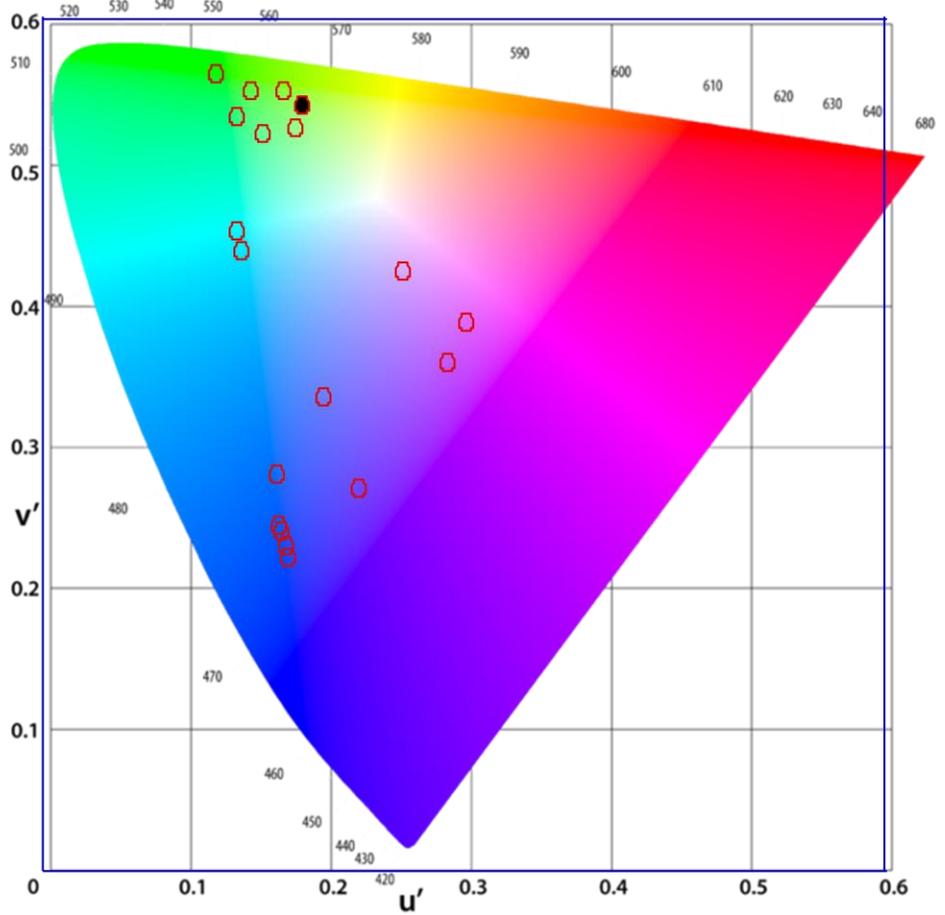
Figure 15. Matches produced to the incongruent frog stimulus graphed in CIE LUV color space. The matches for the incongruent condition exhibit much more variability than the matches for the congruent condition. (Original stimulus chromaticity is represented by the black dot.)
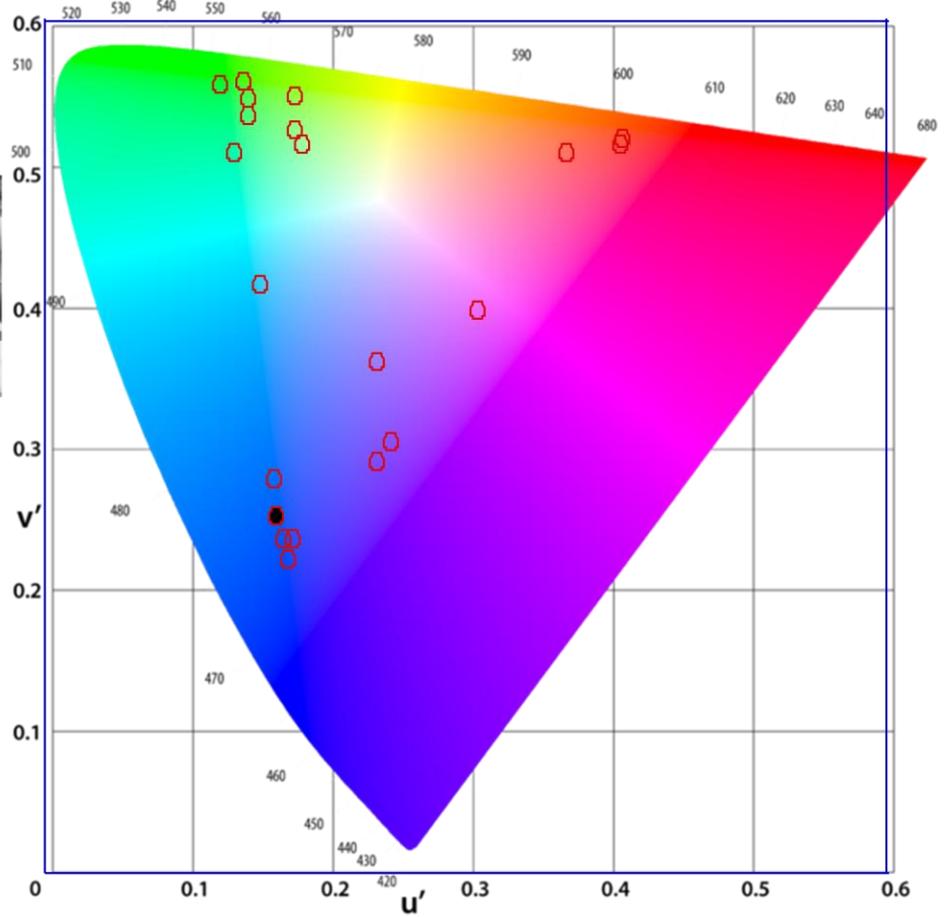
Figure 16. Matches produced to the incongruent strawberries stimulus graphed in CIE LUV color space. The matches for the incongruent condition exhibit much more variability than the matches for the congruent condition. (Original stimulus chromaticity is represented by the black dot.)

Figure 17. Matches produced to the incongruent cotton candy stimulus graphed in CIE LUV color space. The matches for the incongruent condition exhibit much more variability than the matches for the congruent condition. (Original stimulus chromaticity is represented by the black dot.)
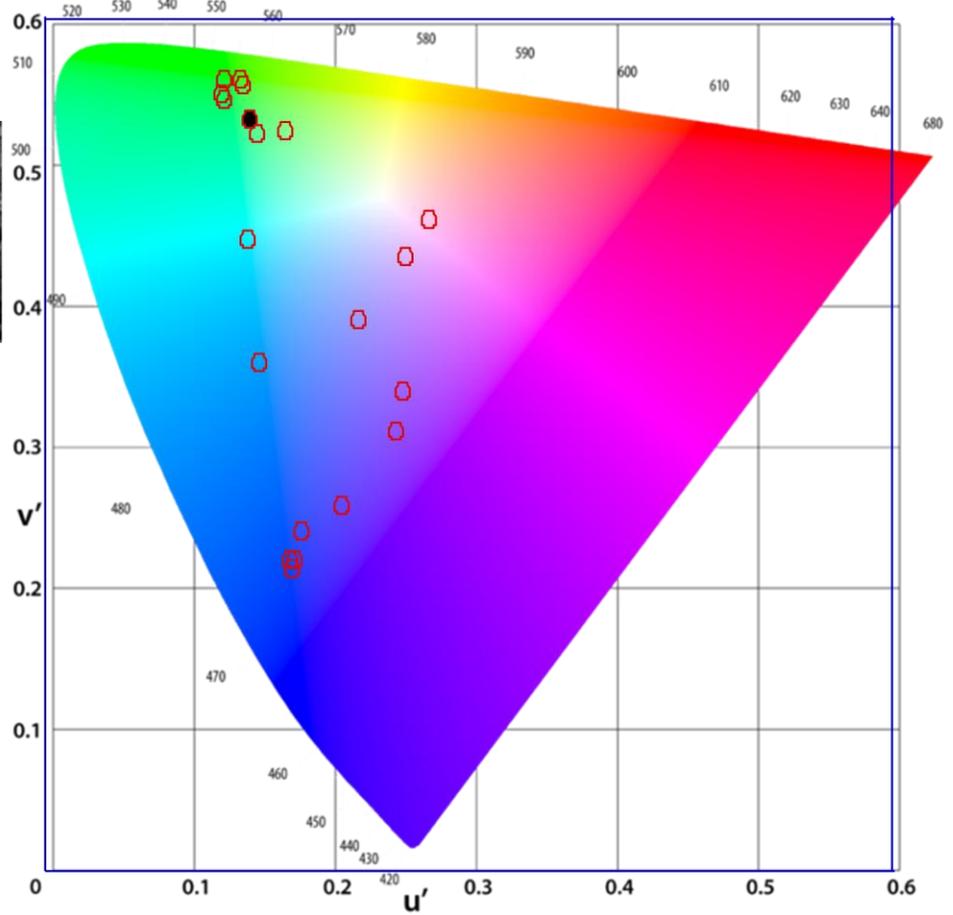
Figure 18. Matches produced to the incongruent rose stimulus graphed in CIE LUV color space. The matches for the incongruent condition exhibit much more variability than the matches for the congruent condition. (Original stimulus chromaticity is represented by the black dot.)

Figure 19. Matches produced to the incongruent chicks stimulus graphed in CIE LUV color space. The matches for the incongruent condition exhibit much more variability than the matches for the congruent condition. (Original stimulus chromaticity is represented by the black dot.)
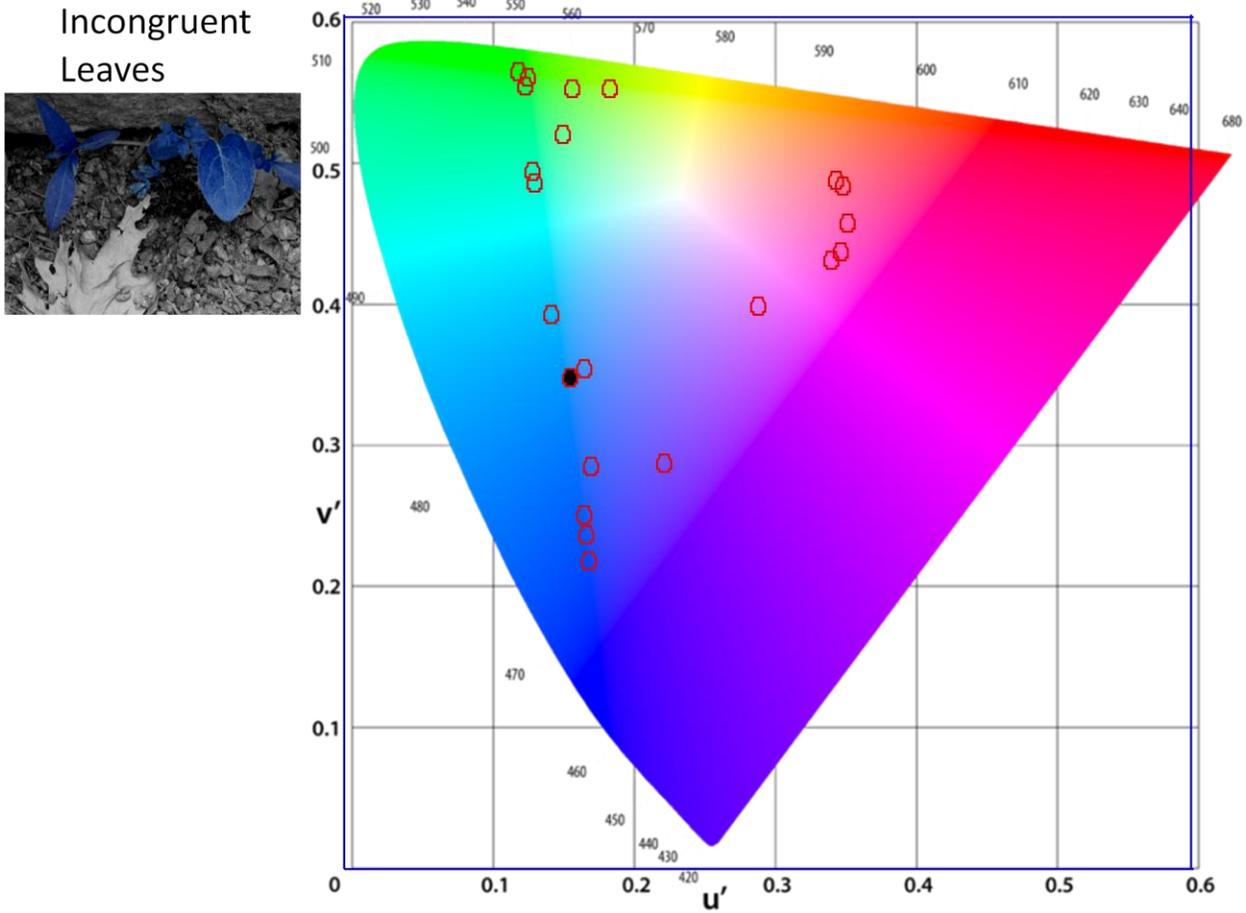
Figure 20. Matches produced to the incongruent leaves stimulus graphed in CIE LUV color space. The matches for the incongruent condition exhibit much more variability than the matches for the congruent condition. (Original stimulus chromaticity is represented by the black dot.)
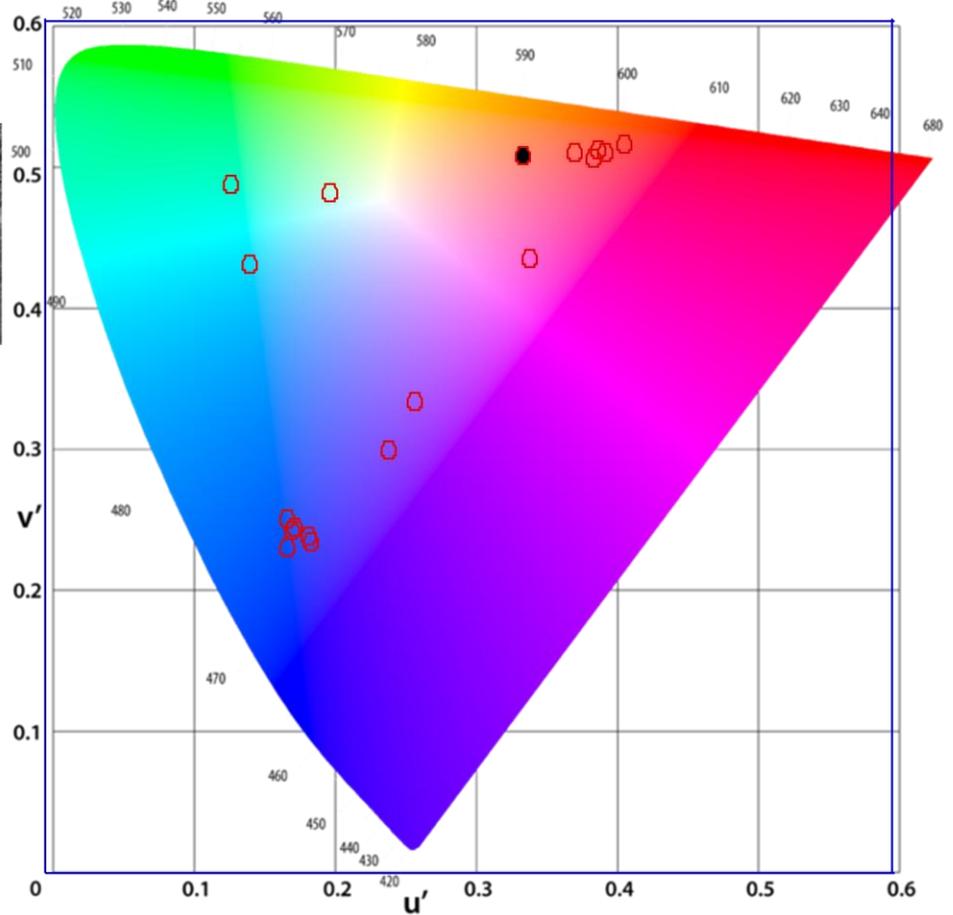
Figure 21. Matches produced to the incongruent tiger stimulus graphed in CIE LUV color space. The matches for the incongruent condition exhibit much more variability than the matches for the congruent condition. (Original stimulus chromaticity is represented by the black dot.)
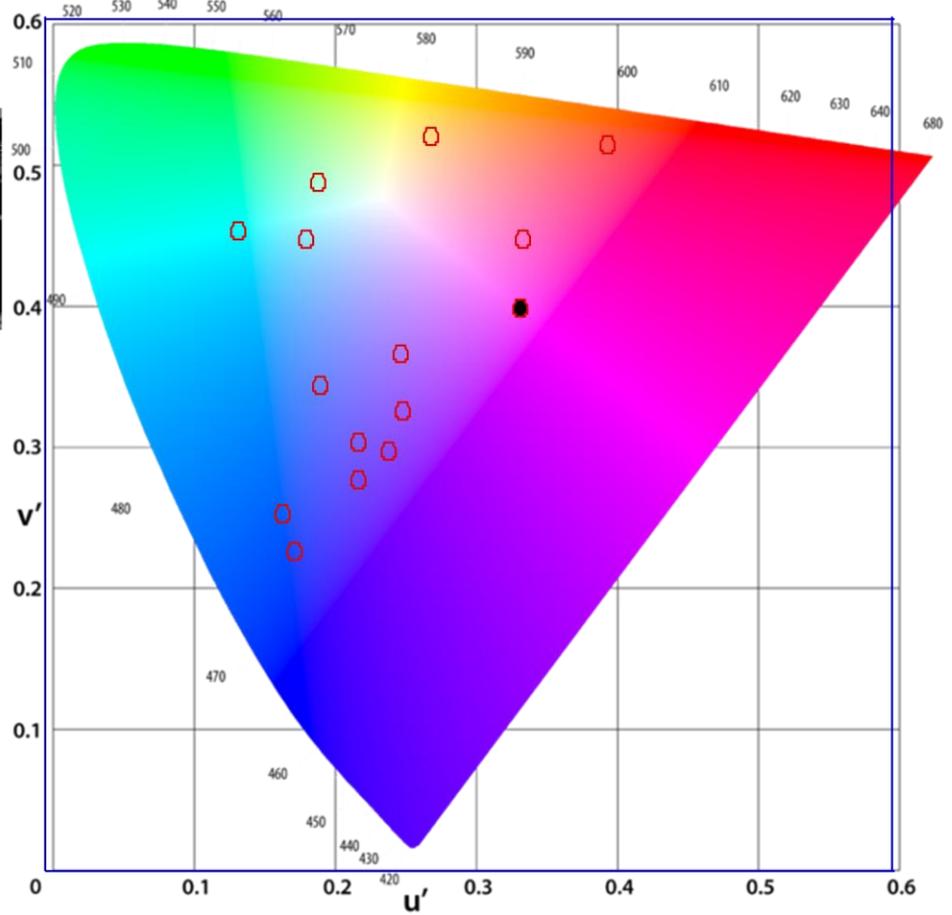
Figure 22. Matches produced to the incongruent strawberries stimulus graphed in CIE LUV color space. The matches for the incongruent condition exhibit much more variability than the matches for the congruent condition. (Original stimulus chromaticity is represented by the black dot.)
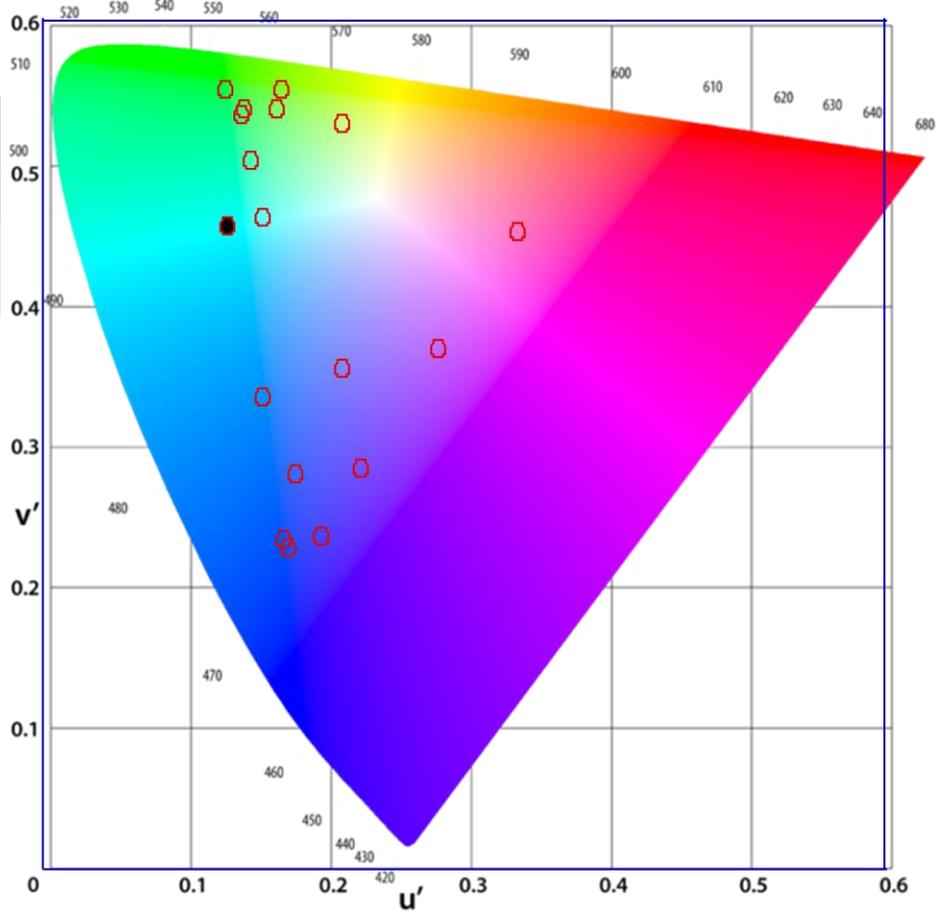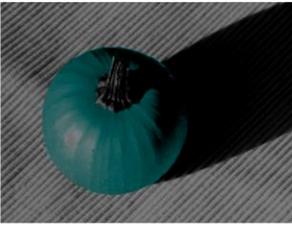
Figure 23. Matches produced to the incongruent pumpkin stimulus graphed in CIE LUV color space. The matches for the incongruent condition exhibit much more variability than the matches for the congruent condition. (Original stimulus chromaticity is represented by the black dot.)
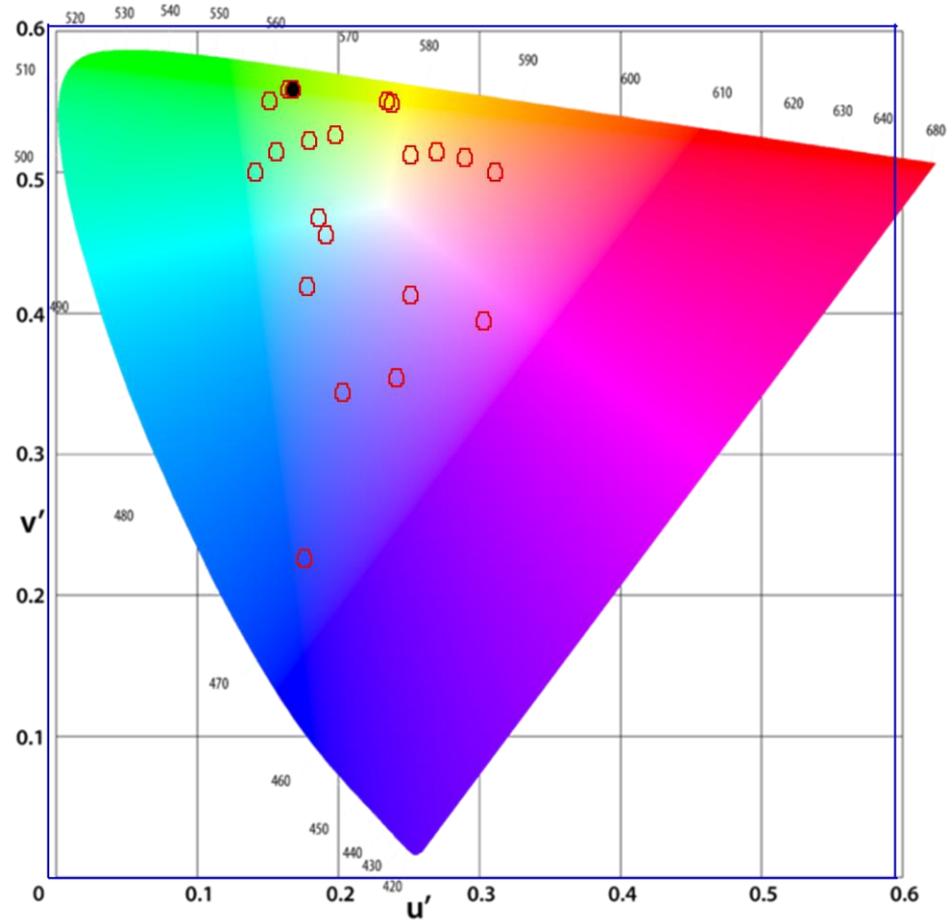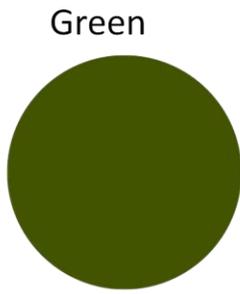
Figure 24. Matches produced for the context-free green stimulus graphed in CIE LUV color space. As participants were able to correctly verbalize the basic color category to which each stimulus belonged, the variability appears to be due to issues with the data collection equipment.
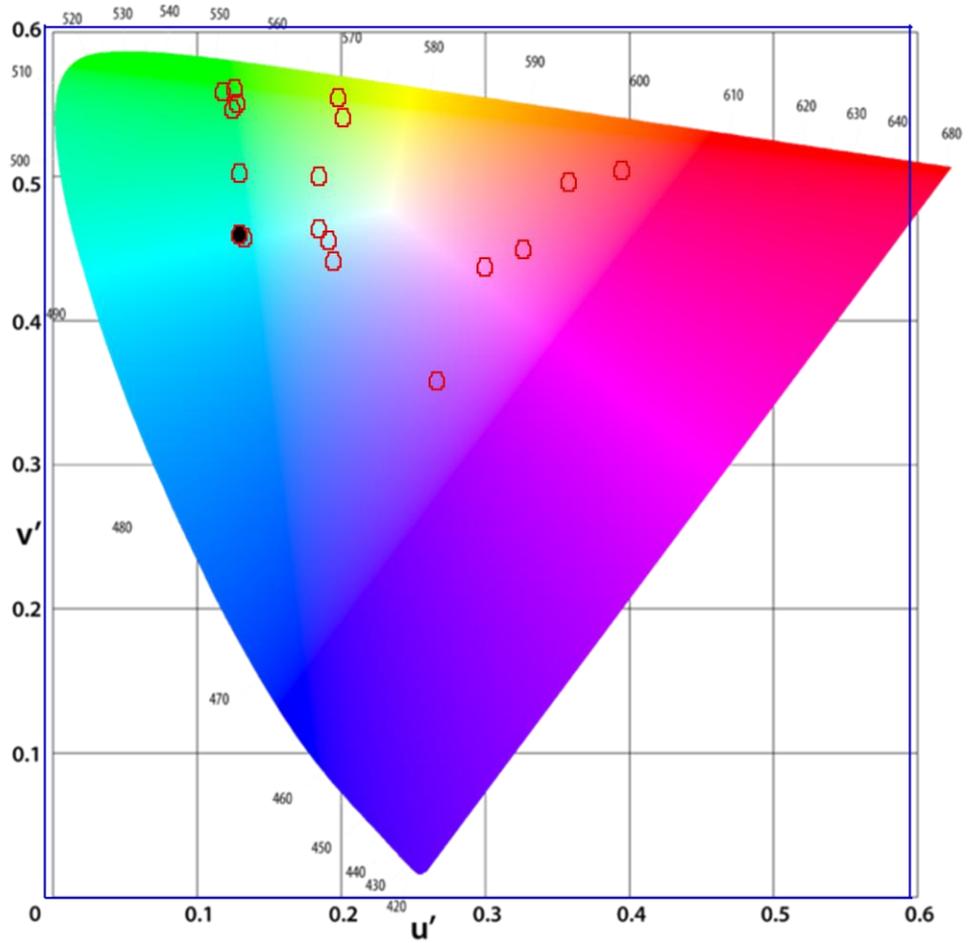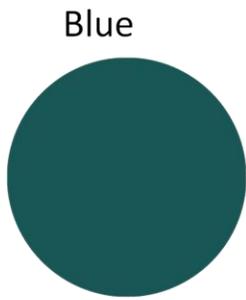
Figure 25. Matches produced for the context-free blue stimulus graphed in CIE LUV color space. As participants were able to correctly verbalize the basic color category to which each stimulus belonged, the variability appears to be due to issues with the data collection equipment.
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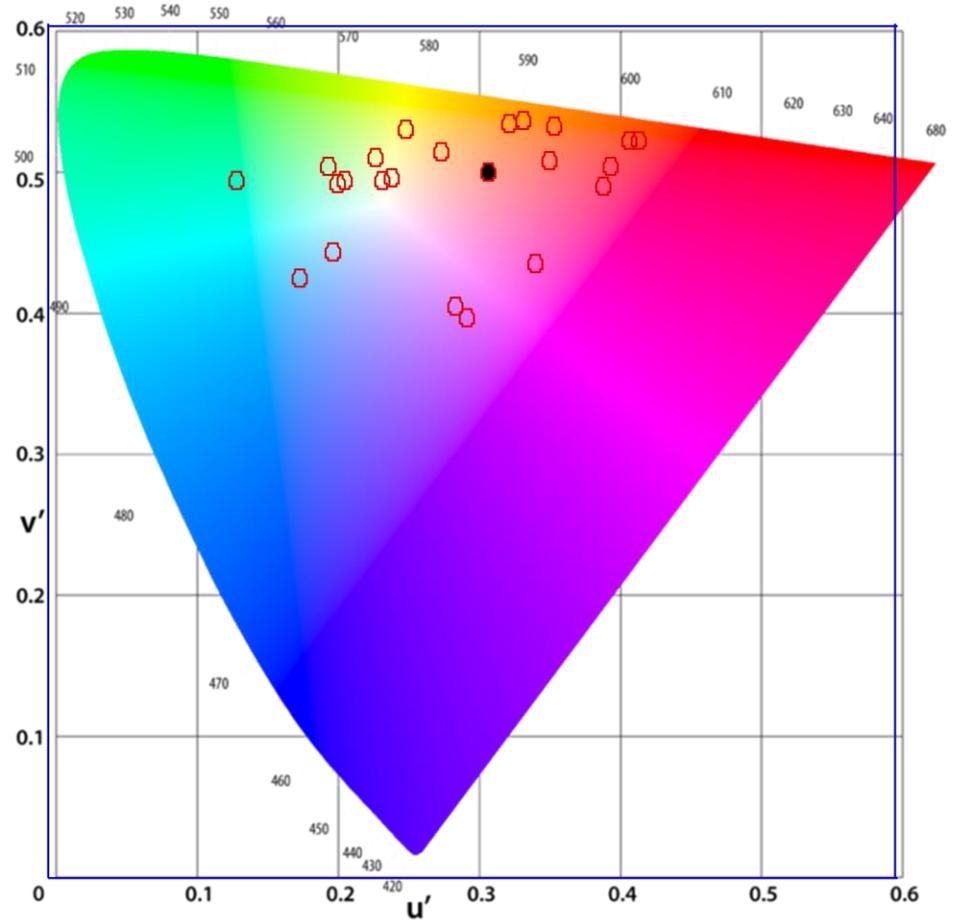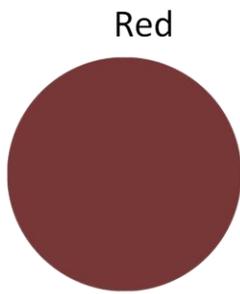
Figure 26. Matches produced for the context-free red stimulus graphed in CIE LUV color space. As participants were able to correctly verbalize the basic color category to which each stimulus belonged, the variability appears to be due to issues with the data collection equipment.

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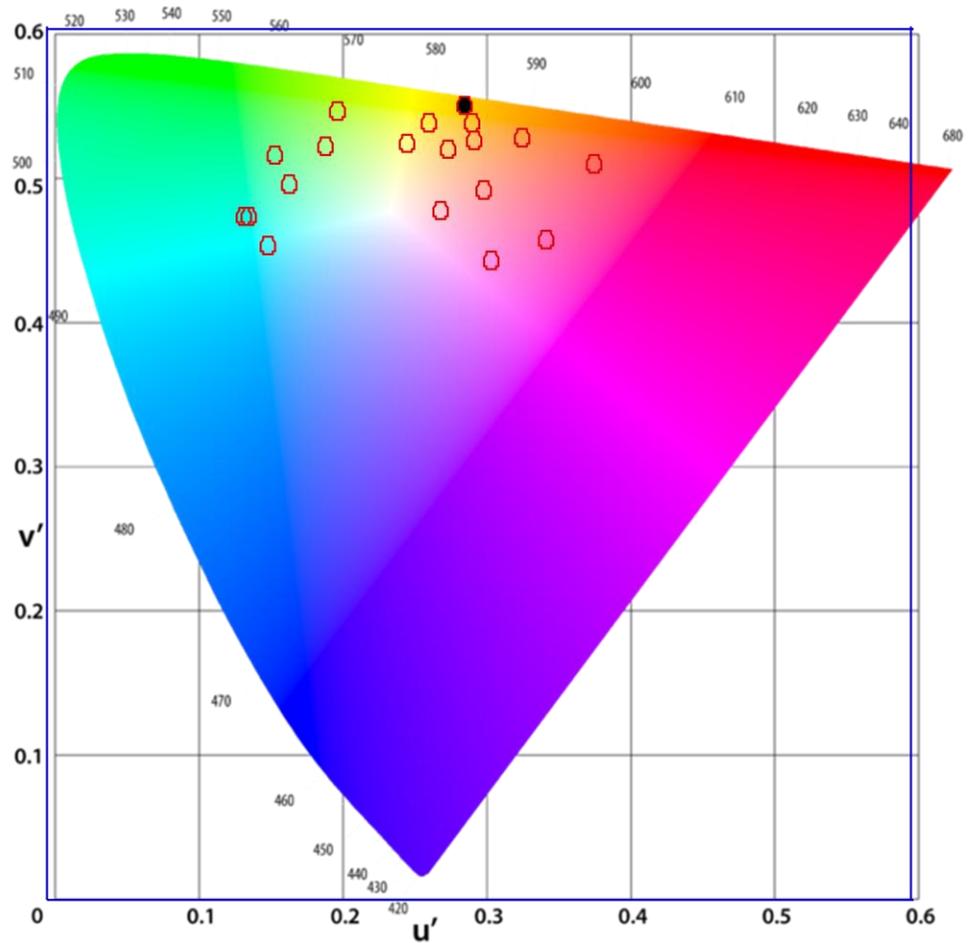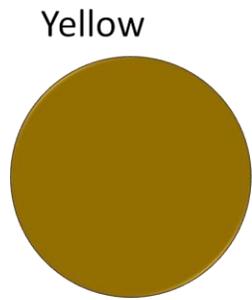
Figure 27. Matches produced for the context-free yellow stimulus graphed in CIE LUV color space. As participants were able to correctly verbalize the basic color category to which each stimulus belonged, the variability appears to be due to issues with the data collection equipment.
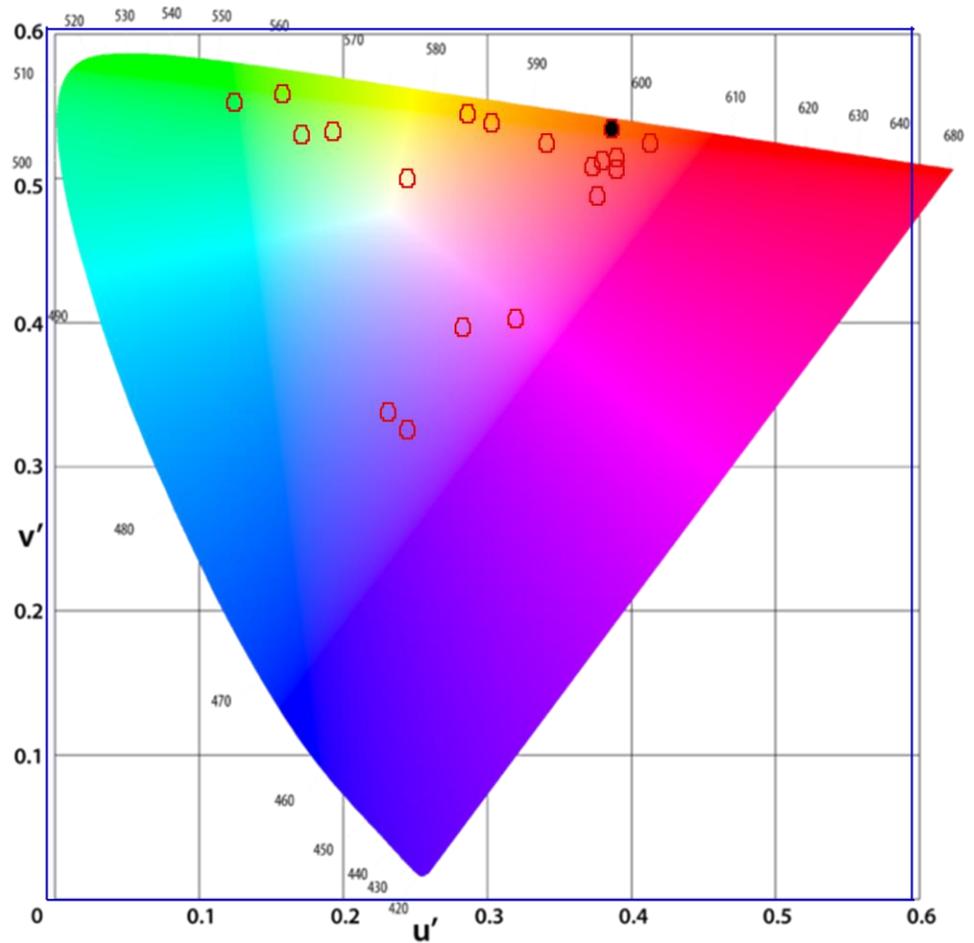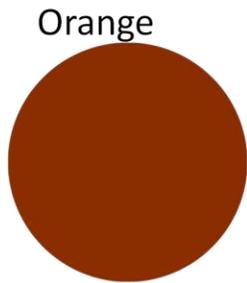
Figure 28. Matches produced for the context-free orange stimulus graphed in CIE LUV color space. As participants were able to correctly verbalize the basic color category to which each stimulus belonged, the variability appears to be due to issues with the data collection equipment.
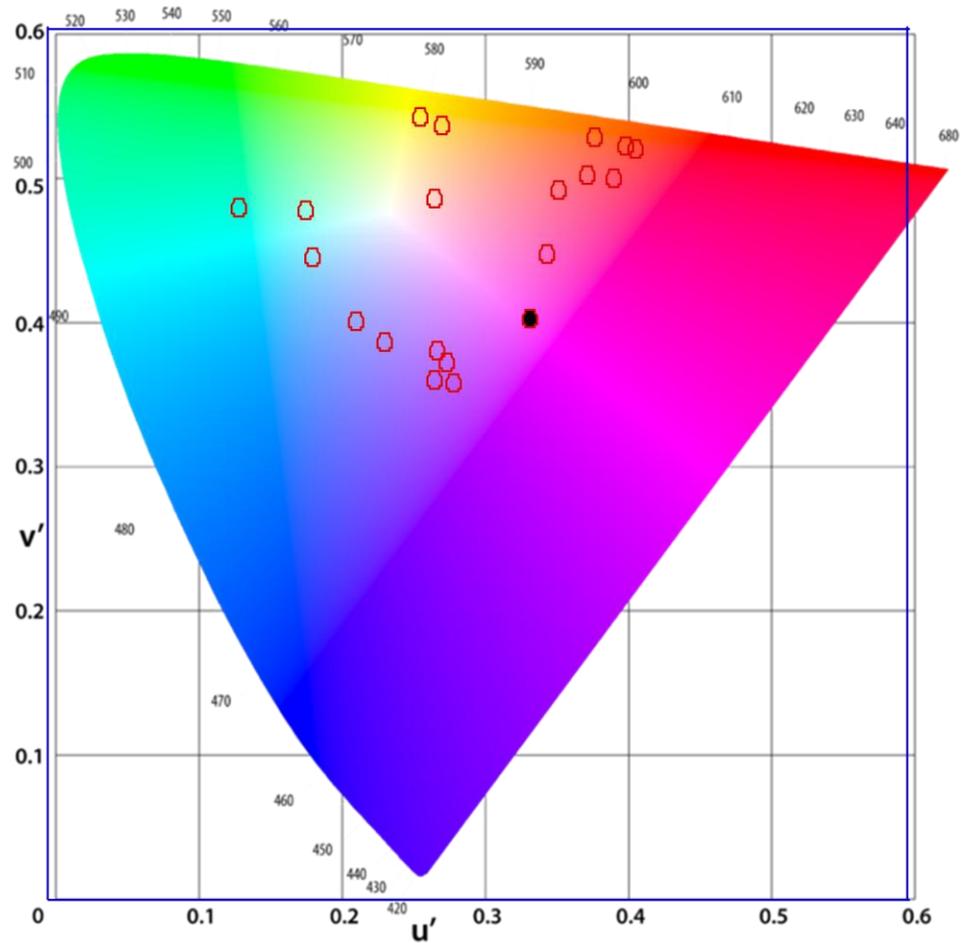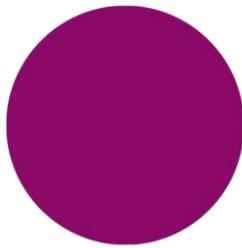
Figure 29. Matches produced for the context-free pink stimulus graphed in CIE LUV color space. As participants were able to correctly verbalize the basic color category to which each stimulus belonged, the variability appears to be due to issues with the data collection equipment.
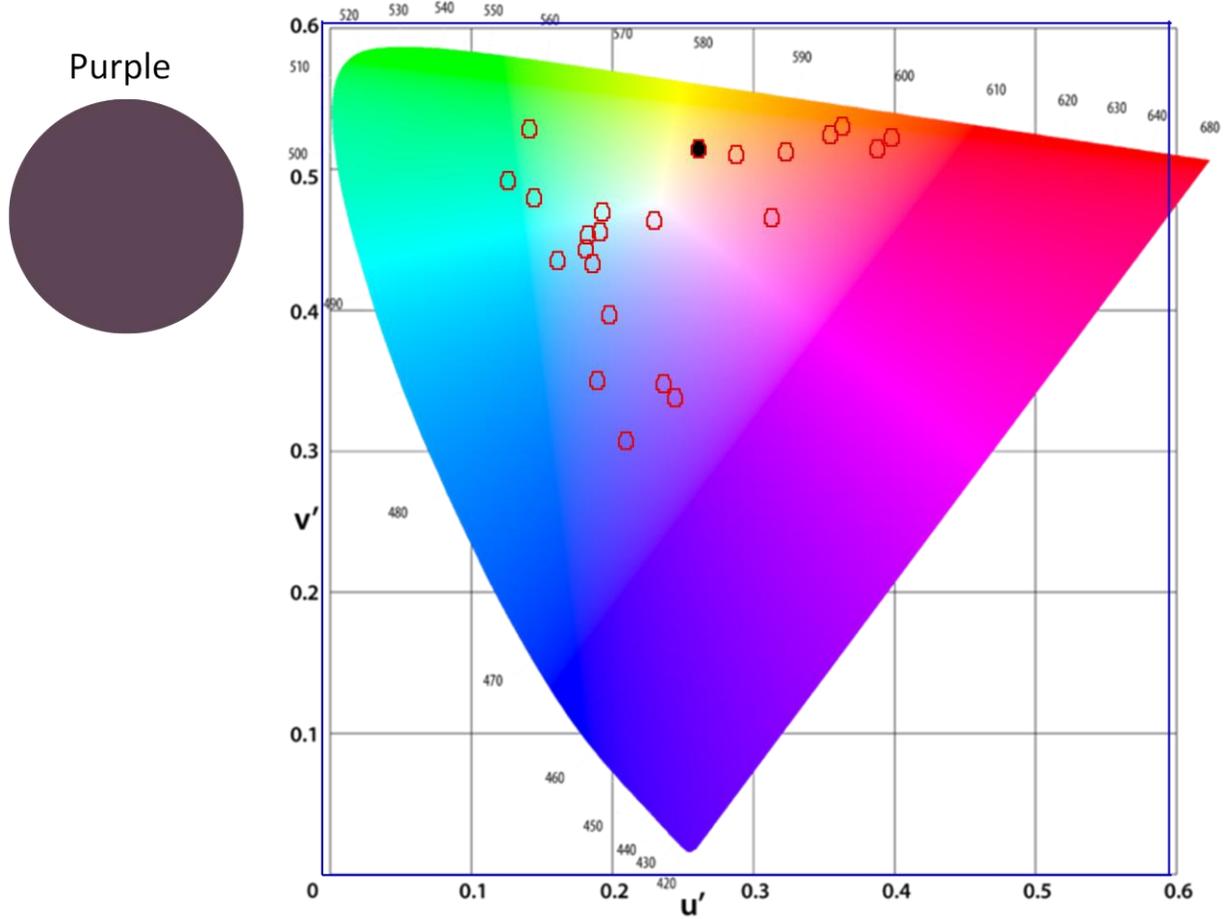
Figure 30. Matches produced for the context-free purple stimulus graphed in CIE LUV color space. As participants were able to correctly verbalize the basic color category to which each stimulus belonged, the variability appears to be due to issues with the data collection equipment.
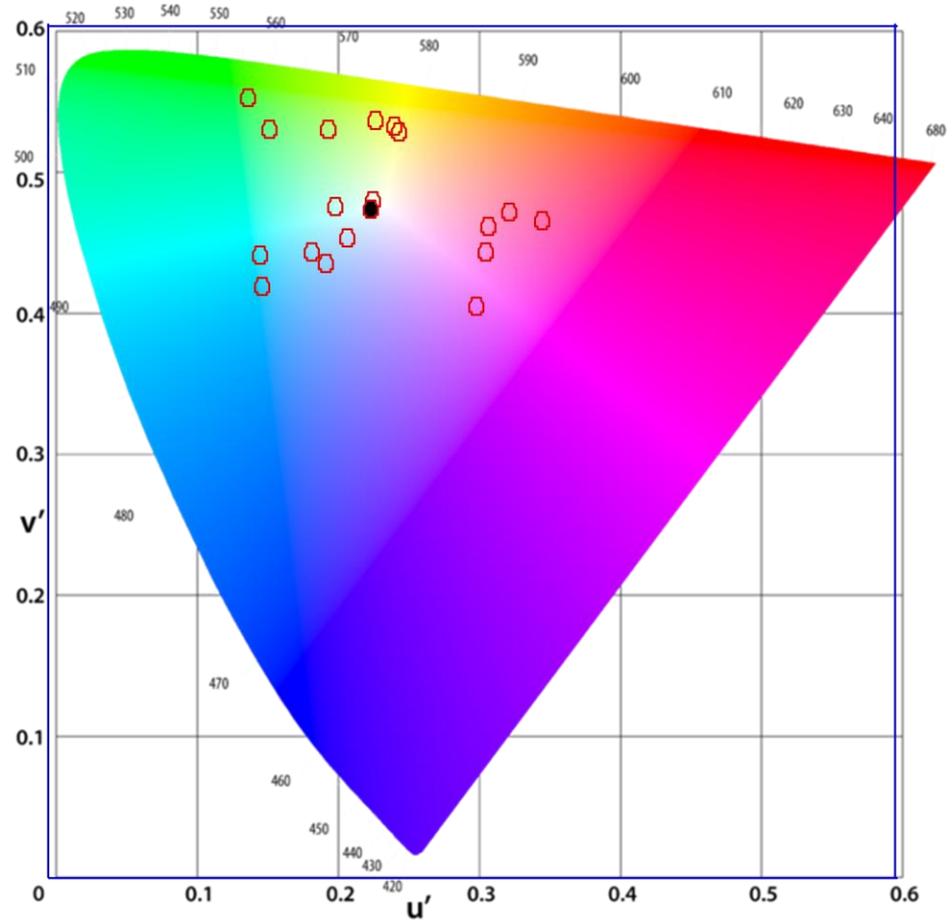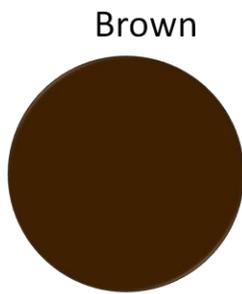
*Figure 31.* Matches produced for the context-free brown stimulus graphed in CIE LUV color space. As participants were able to correctly verbalize the basic color category to which each stimulus belonged, the variability appears to be due to issues with the data collection equipment.
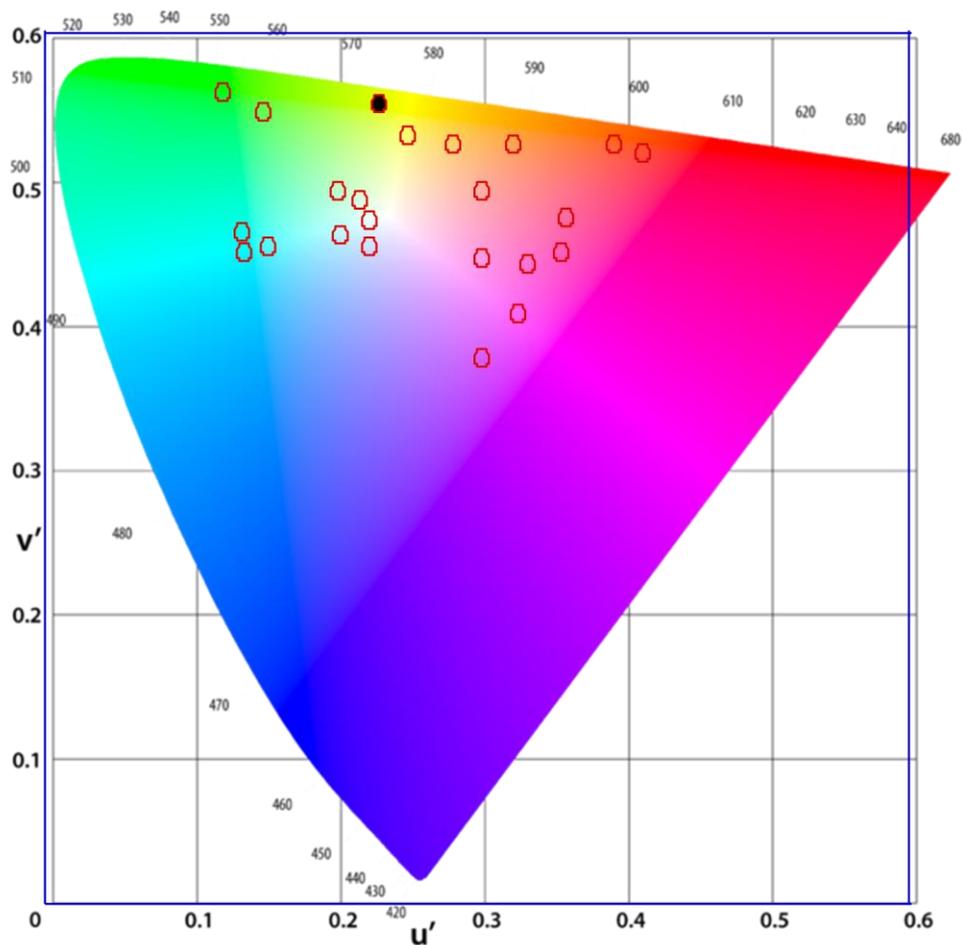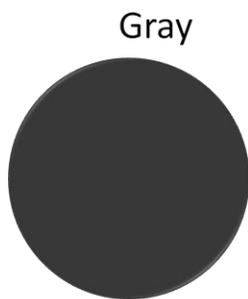
Figure 32. Matches produced for the context-free gray stimulus graphed in CIE LUV color space. As participants were able to correctly verbalize the basic color category to which each stimulus belonged, the variability appears to be due to issues with the data collection equipment.

Table 1

Multiple Linear Regression to Predict Vector Length (n = 592)

Variable	B	SE(B)	β	t	p
Intercept	.310	.015	-----	20.952	.000
Congruent Slideshow	-.008	.021	-.026	-.386	.700
Incongruent Slideshow	.025	.021	.079	1.183	.237
Delay Condition	.012	.020	.041	.600	.549
Congruent by Delay	.015	.030	.037	.504	.615
Incongruent by Delay	.025	.029	.064	.867	.387

Note. R^2 = 0.023. Context-free slideshow used as reference group.

Table 2

Multiple Linear Regression to Predict Confidence (n = 592)

Variable	B	SE(B)	β	t	p
Intercept	52.906	2.175	-----	24.321	.000
Congruent Slideshow	16.146	3.152	.337	5.122	.000
Incongruent Slideshow	13.717	3.076	.289	4.459	.000
Delay Condition	2.333	3.005	.052	.776	.438
Congruent by Delay	-7.342	4.361	-.122	-1.684	.093
Incongruent by Delay	-10.250	4.306	-.171	-2.380	.018

Note. R^2 = 0.069. Context-free slideshow used as reference group.

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