# Colors in mind: A novel paradigm to investigate pure color imagery

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**Abstract**

Mental color imagery abilities are commonly measured using paradigms that involve naming, judging or comparing the colors of visual mental images of well-known objects (e.g., “is a sunflower darker yellow than a lemon”?). Although this approach is widely used in patient studies, differences in the ability to perform such color comparisons might simply reflect participants’ general knowledge of object colors rather than their ability to generate accurate visual mental images of the colors of the objects. The aim of the present study was to design a new color imagery paradigm. Participants were asked to visualize a color for 3 s and then to determine a visually presented color by pressing one of six keys. We reasoned that participants would react faster when the imagined and perceived colors were congruent than when they were incongruent. In Experiment 1, participants were slower in incongruent than congruent trials but only when they were instructed to visualize the colors. The results in Experiment 2 demonstrate that the congruency effect reported in Experiment 1 cannot be attributed to verbalization of the color that had to be visualized. Finally, in Experiment 3, the congruency effect evoked by mental imagery correlated with performance in a perceptual version of the task. We discuss these findings with respect to the mechanisms that underlie mental imagery and patients suffering from color imagery deficits.


*Keywords: mental imagery, color imagery, chromatic imagery*

## Introduction

Imagine your mind's eye to be greyscale. How would you find out whether some pillows in a shop match the color of the couch in your living room? How would you know that you would like the dress of your friend better if only it had a different color? Mental imagery of color is part of real life cognitive activity. However, as De Vreese (1991) pointed out, due to methodological obstacles, color imagery has hitherto not received much attention especially in healthy participants.

To date, most studies have focused on impairments of color imagery following brain lesions. Color imagery was measured in tasks requiring patients to name or select colors of common objects (Bartolomeo, Bachoud-Levi, & Denes, 1997; Chatterjee & Southwood, 1995; De Vreese, 1991; Luzzatti & Davidoff, 1994; Manning, 2000; Shuren, Brott, Schefft, & Houston, 1996), to decide whether a specific color is appropriate for a common object (Goldenberg, Müllbacher, & Nowak, 1995; Zago, Corti, Bersano, Baron, Conti, Ballabio, et al., 2010), to mentally compare the hues of different objects (Bartolomeo, et al., 1997; Chatterjee & Southwood, 1995; De Vreese, 1991; Luzzatti & Davidoff, 1994; Shuren, et al., 1996; Zago, et al., 2010), to name as many objects of a particular color (Bartolomeo, et al., 1997; De Vreese, 1991) or to produce as many color names as possible (Bartolomeo, et al., 1997). The findings from these studies converge in showing a double dissociation between color perception and color imagery: some patients have impaired color imagery but intact color perception (Bartolomeo, et al., 1997; Chatterjee & Southwood, 1995; Goldenberg, et al., 1995; Luzzatti & Davidoff, 1994; Shuren, et al., 1996; Zago, et al., 2010) while others have impaired color perception but intact color imagery (De Vreese, 1991; Goldenberg, 1992; Manning, 2000).

This double dissociation between color imagery and color perception is rather surprising given the huge overlap in brain activation that was found in mental imagery and perception of objects (e.g., O'Craven & Kanwisher, 2000; Ishai, Ungerleider, & Haxby, 2000, Ishai, Haxby, & Ungerleider, 2002, Kosslyn, Thompson, Kim, & Alpert, 1995; Slotnick, Thompson, & Kosslyn, 2005; for a review see Kosslyn & Thompson, 2003). Indeed, the results of neuroimaging studies with healthy participants on the degree of overlap of the brain areas activated in color perception and color imagery remain largely inconclusive. Some studies reported that object color retrieval elicits activation in the same areas as the ones activated in color perception, notably in color selective visual areas such as V4 (Hsu, Frankland, & Thompson-Schill, 2012; Hsu, Kraemer, Oliver, Schlichting, & Thompson-Schill, 2011; Rich, Williams, Puce, Syngeniotis, Howard, McGlone, et al., 2006; Simmons, Ramjee, Beauchamp, McRae, Martin, & Barsalou, 2007). Conversely, other neuroimaging studies did not report a functional overlap between color imagery and perception (Bramao, Faisca, Forkstam, Reis, & Petersson, 2010; Chao & Martin, 1999; Howard, Ffytche, Barnes, McKeefry, Ha, Woodruff, et al., 1998; Lu, Xu, Jin, Mo, Zhang, & Zhang, 2010; Miceli, Fouch, Capasso, Shelton, Tomaiuolo, & Caramazza, 2001).

A possible reason for the discrepancy in the literature might be the varying extent to which the tasks used to measure the ability to visualize color did actually involve color imagery. First, answering a question such as “what color is a lime?” might not rely exclusively on the ability to generate an accurate visual mental image of a lime in color but also on semantic knowledge about this object (i.e., color knowledge). Moreover, some color terms are tightly linked to colors in a linguistic fashion (e.g., we refer to bright lucent green as “lime green”). Some researchers have argued that both visual and/or verbal processes contribute to color knowledge (Beauvois & Saillant, 1985) and that these processes might be hard to distinguish in tasks in which participants need to determine the typical color of an object (De Vreese, 1991). Second, mental hue comparison tasks such as “is a strawberry darker red than a tomato?” can be solved with greyscale imagery. Third, the tasks designed to date do not necessarily tap into pure color imagery but also involve the visualization of shape and other attributes of the objects (Chang, Lewis, & Pearson, 2013). Last but not least, most of these tasks are easy to solve, especially for participants with no color knowledge impairments. Thus, the available tasks may not be subtle enough to assess individual color imagery abilities of healthy participants.

Recently, Chang et al. (2013) developed the first paradigm to measure pure color imagery in the absence of object imagery. Participants were instructed to imagine a cued color, just thereafter two colors were presented binocularly and participants judged which of the two colors they perceived. Participants more often indicated to perceive the color that they just imagined. It is unclear, however, whether this effect reflects an influence of color imagery on perception due to shared mechanisms or whether the same results could have been obtained by simply verbally repeating the color rather than visualizing the color before the binocular rivalry display was presented.

The present study aimed at developing a refined pure color imagery paradigm. The principle of this paradigm relies on the classical finding that visual mental imagery modulates subsequent perception of visual stimuli (Chang, et al., 2013; Ishai & Sagi, 1995; Pearson, Rademaker, & Tong, 2008; Perky, 1910). Participants were first instructed to visualize a color in a blank box indicated either by the presentation of a greyscale picture of an object (i.e., lemon) or by the two first letters of the color to visualize. After the visualization period, a color was displayed in that box. Participants were instructed to determine the visually presented colors as fast and accurately as possible by pressing one of six keys. We expected shorter reaction times on trials where the visualized color matched the presented color (i.e., congruent trials) when compared to trials where the visualized color did not match the presented color (i.e., incongruent trials). In Experiment 1, we asked two groups of participants to perform this task. One group was instructed to visualize the colors in response to the two cue types (i.e., objects or first two letters of the color name). The other group received no instruction to generate mental images of colors (control group). If color mental imagery modulates reaction times in a subsequent color identification task then participants in the mental imagery group but not in the control group should be faster to identify the color in congruent trials than in incongruent trials. Experiment 2 was conducted in order to exclude the possibility that the congruency effect reported in Experiment 1 (i.e., shorter response times for congruent compared to incongruent trials) could be due to verbal priming. Finally, in Experiment 3, we investigated whether individual differences in the congruency effects in the mental imagery task were related to the congruency effects in a perceptual version of this task (i.e., a color was displayed visually preceding the visual presentation of the color to identify). We reasoned that if color imagery functionally overlaps with color perception, the congruency effects in these two versions of the tasks should be correlated.

# Experiment 1

## Methods

**Participants.** Thirty-two participants (28 females) ranging in age between 19 and 47 years ($M$ = 24.75, $SD$ = 6.525) were recruited from the Department of Psychology at the University of Bern and received course credits for their participation. They were informed that the study was about color imagery and color perception. All participants confirmed not to be color-blind. They all gave written informed consent to participate prior to the experiment and were treated in accordance with the ethical protocol approved by the Faculty of Human Sciences of the University of Bern and the “Ethical Principles of Psychologists and Code of Conduct” of the American Psychological Association (2002).

**Material.** We designed two imagery cue types (letters, objects). In the letter condition, we used the first two letters of the colors (e.g., “gr” for green) in 18 pt black Courier font on a white background. Since a color word might automatically activate color concepts (as in the classical Stroop task, Stroop, 1935), we presented only the first two letters of the cue word. Because two color words used in the experiment start with the same letter in German (the language in which the experiment was conducted), we presented not only the first but the first two letters of the color words. The background was white (min luminance = 38.2 cd/m$^2$, max luminance = 41.4 cd/m$^2$, mean[1] = 255) throughout the experiment. In the object condition, six standardized black and white objects from the bank of standardized stimuli (BOSS; Brodeur, Dionne-Dostie, Montreuil & Lepage, 2010) were used, which were explicitly related to one of the six visually presented colors (lemon (min luminance = 5.41 cd/m$^2$, max luminance = 20.4 cd/m$^2$, mean = 134.10), orange (min luminance = 3.82 cd/m$^2$, max luminance = 11.38 cd/m$^2$, mean = 112.77), tomato (min luminance = 2.3 cd/m$^2$, max luminance = 10.4 cd/m$^2$, mean = 72.93), eggplant (min luminance = 0.55 cd/m$^2$, max luminance = 5.69 cd/m$^2$, mean = 40.33), lettuce (min luminance = 1.25 cd/m$^2$, max luminance = 16.9, mean = 89.92), walnut (min luminance = 2.62 cd/m$^2$, max luminance = 7.40 cd/m$^2$, mean = 88.64)). It is possible that black and white object images automatically activate color concepts because they are concrete. Thus, we also included letter cues, which are less likely to trigger automatic processes and conceptual biases. Using both types of cues allows for comparing possible influences of automatic concept activation. Participants visualized one of six colors (yellow, orange, red, purple, green, brown) in response to the letters or object cues within a blank square. After participants visualized one of the six colors in the blank box, a colored square of the same size was presented visually. We chose the following six colors (and corresponding RGB and luminance values): yellow (255, 251, 0; min luminance = 33.9 cd/m$^2$, max luminance = 36.3 cd/m$^2$, mean = 225), orange (230, 150, 0; min luminance = 20.3 cd/m$^2$, max luminance = 21.9 cd/m$^2$, mean = 158), red (255, 37, 0; min luminance = 10.8 cd/m$^2$, max luminance = 11.6 cd/m$^2$, mean = 98), purple (70, 30, 90; min luminance = 1.46 cd/m$^2$, max luminance = 1.59 cd/m$^2$, mean = 49), green (1, 128, 0; min luminance = 9.07 cd/m$^2$, max luminance = 9.54 cd/m$^2$, mean = 76) and brown (139, 69, 19; min luminance = 5.23 cd/m$^2$, max luminance = 5.47 cd/m$^2$, mean = 84). The viewing angle of the greyscale pictures of objects, the blank square and the colored squares was approximately 10.7°.

[1] Mean was derived from luminance histogram in Adobe Photoshop CS6.

**Procedure.** Participants were tested in pairs in separate cubicles so that they did not see each other's computer screen. Data was collected using E-Prime v1.2 (Psychology Software Tools INC., Pittsburgh, USA; www.pstnet.com/prime). Participants performed two blocks of trials, one with letters and one with greyscale pictures of objects as cues. The order of the two blocks was counterbalanced across participants. Each block consisted of 100 trials without break. There was a short, non-paced break between the two blocks (approximately 3 minutes).

Each trial started with a fixation cross, followed by a cue (first two letters of a color word or a greyscale picture of an object) and an inter stimulus interval of 500 ms each. Then a blank square was presented for 3000 ms. Both groups were briefed that the letter cues corresponded to the first two letters of a color word. However, only the imagery group was instructed to mentally visualize the cued color during presentation of the blank box whereas the control group was just instructed to wait until the color target appears. Finally, a colored square replaced the blank square and participants were asked to determine the color of the square presented by pressing one of six keys as quickly and accurately as possible. The procedure is illustrated in Figure 1. To facilitate key-response mapping, the six keys were laminated with colored paper that was visible even when the fingers were placed on the respective keys ("x" = yellow, "c" = orange, "v" = red, "b" = purple, "n" = green, "m" = brown). This assignment was the same for all participants in all experiments. Participants used their left ring, middle and index finger for the yellow, orange and red keys and their right index, middle and ring finger for the purple, green and brown keys. There was no feedback throughout the experiment.

Importantly, congruent trials were defined as trials in which the cued color and the color presented visually matched (e.g., tomato-red). In incongruent trials, the cued and displayed color did not match (e.g., lemon-purple). In each block, the same amount of congruent and incongruent trials (50 trials each) appeared in randomized order. Participants were randomly assigned to either the mental imagery or the control group and to one of two task sequence conditions (object cues first, letter cues first). Reaction times (i.e., time between the onset of the color square and the button-press) and accuracy were recorded. In order to compare the results of our color imagery task with standard measures of general visual imagery vividness and to control for group differences in standard imagery tests, all participants completed a computer-based version of the vividness of visual imagery questionnaire (VVIQ; Cui, Jeter, Yang, Montague & Eagleman, 2007; Marks, 1973) after the color identification task.

## Results

Given that no practice block was performed, we excluded the first 10 trials of each task. For the reaction time analysis, we only included values of correctly solved trials and we discarded values that deviated more than three standard deviations from each participant's mean (1.08% of the remaining trials). Errors occurred in less than 6% of the trials and did not differ as a function of condition. We computed a mixed-design analysis of variance (ANOVA) with the within-participant factors cue type (i.e., letters vs. objects trials) and congruency (i.e., congruent vs. incongruent trials) and the between-participant factor group (mental imagery vs. control).

The descriptive data of the reaction times can be found in Table 1 and are depicted in Figure 2. Whereas neither the cue type, $F<1$, nor the group, $F(1, 30) = 1.87$, $p = .18$, had an effect on reaction times, there was a significant main effect of congruency, $F(1, 30) = 25.04$, $p < .001$, $\eta_p^2 = .46$). Bonferroni corrected post-hoc comparisons confirmed that participants were generally faster on congruent compared to incongruent trials ($p < .001$). As expected, the effect of the congruency varied in the two groups as revealed by a significant congruency group interaction, $F(1, 30) = 9.02$, $p < .005$, $\eta_p^2 = .23$. Paired samples t-tests revealed that the experimental group was significantly faster on congruent compared to incongruent trials ($t(15) = -4.94$, $p < .001$, $d = 1.24$) whereas the control group did not show such an effect

($t(15) = -1.71$, $p = .108$). No other two- or three-way interactions reached significance (all *ps* > .18). A similar three-way mixed-design ANOVA on the accuracy data revealed no significant main effects or interactions (all *ps* > .062, see Table 2 for mean accuracy) suggesting that the reaction times cannot be explained by a speed-accuracy tradeoff.

One could speculate that the congruency effect in the object cue trials reflects luminance congruency between cues and targets rather than effects of color imagery. If this were the case, the same congruency effect would emerge even when participants simply visualize the black and white object cue. To test this hypothesis, we correlated mean luminance differences between object cues and color targets and reaction times on a trial-by-trial basis. Indeed, there was a significant correlation in the imagery group ($r(1369) = .086$, $p = .001$), however, this relationship was absent in the control group ($r(1383) = .021$, $p = .438$).

In order to test the reliability of this task, a bivariate Pearson correlation was calculated between the congruency effects (reaction times of incongruent – congruent trials) of the first and second half of the task in the experimental group. The results revealed a high reliability ($r(14) = .94$, $p < .001$). The mean VVIQ score was $M = 2.195$, $SD = .483$ in the experimental group and $M = 2.395$, $SD = .606$ in the control group. This difference was not significant ($t(30) = -1.028$, $p = .751$). Finally, we computed bivariate Pearson correlations between the individual congruency effects (reaction times on incongruent – reaction times on congruent trials, across cue type conditions) and the VVIQ scores in the experimental group. These results revealed no significant correlation, $r(14) = .11$, $p = .69$).

**Discussion**

Consistent with our hypotheses, we showed that visualizing colors influences subsequent color identification reaction times. The reaction time difference between congruent and incongruent trials was larger in the group that was instructed to mentally visualize colors than in the control group. Moreover, the reliability of the color imagery task was high, as indicated by the correlation between the congruency effects in the first and second half of the task.

It could be argued that the mental imagery task we designed did not necessarily require participants to visualize colors – that is to generate depictive representations of the colors (Kosslyn, 2005). Possibly, the same response pattern could emerge from inner verbalization of the colors. Assuming that participants were silently repeating "red...red…red…" after being cued with a tomato, they could have been just as slow when having to determine the color of a green patch right afterwards. Pylyshyn's (1973) propositional theory suggests that the propositional features of the word "red" would prime participants to process the color red faster on congruent trials. We conducted a second experiment to determine whether the same congruency effect as the one reported in Experiment 1 would replicate in a condition in which verbal priming could not occur.

## Experiment 2

In Experiment 2, participants were asked to perform the same task as in Experiment 1 either in the mental imagery condition or the control condition (i.e., with no imagery instruction) while performing a concurrent articulatory suppression task (i.e., repeating 'ba' during the presentation of the blank box). The concurrent articulatory suppression task prevented phonological encoding of the colors (a similar procedure has been used by Brandimonte, Hitch, & Bishop, 1992, in the context of a short-term memory task). We reasoned that if the congruency effect found in Experiment 1 was due to visualization of the color rather than due to inner verbalization of the color name, then the congruency effect should be found even when participants performed an articulatory suppression task while they were imagining the color.

### Methods

**Participants.** Thirty-two participants (18 female) ranging in age between 19 and 52 years ($M$ = 25.38, $SD$ = 8.4) were recruited from the Department of Psychology of the

University of Bern. There was no compensation for participation in the study. Participants were randomly assigned to either the mental imagery or the control group. All participants confirmed not to be color-blind. They all gave written informed consent to participate prior to the experiment and were treated in accordance with the ethical protocol approved by the Faculty of Human Sciences of the University of Bern and the “Ethical Principles of Psychologists and Code of Conduct” of the American Psychological Association (2002).

**Material.** The material was identical to the one used in Experiment 1.

**Procedure.** The procedure was identical to the one in Experiment 1, except that participants in both groups were given the instruction to repeat the syllables ‘ba...ba...ba...’ out loud during the presentation of the blank box. In contrast to Experiment 1, participants were tested individually.

**Results**

As in Experiment 1, we excluded the first 10 trials of each task. Of all correctly solved trials, we then excluded responses that deviated more than three standard deviations from each participant’s mean (1.09% of the remaining trials). Errors occurred in less than 9% of the trials and did not differ as a function of condition. One participant was excluded from the data analysis because his reaction times were more than 2.5 SD from the mean of the group. As in Experiment 1, we analyzed the reaction times by means of a mixed-design ANOVA with the within-participant factors cue type (i.e., letters vs. objects trials) and congruency (i.e., congruent vs. incongruent trials) and the between-participant factor group (mental imagery vs. control).

As shown in Figure 3 (see also Table 1), there was no effect of the cue type, $F(1, 28) = 2.456$, $p = .128$, or the group, $F < 1$. However, there was a main effect of congruency, $F(1, 28) = 65.991$, $p < .001$, $\eta_p^2 = .70$. Bonferroni corrected post-hoc comparisons revealed that participants were significantly faster on congruent compared to incongruent trials ($p < .001$). A significant two-way interaction, $F(1, 28) = 8.476$, $p = .007$, $\eta_p^2 = .23$ shows that the congruency effect was larger in the mental imagery than the control group. There were no other significant two-way or three-way interactions (all *ps* $> .305$). A similar three-way ANOVA on the accuracy rate revealed no main effects or interactions (all *ps* $> 0.78$, see Table 2), suggesting that no speed-accuracy tradeoff could account for the effect reported on the reaction times.

In order to check influences of object cue luminance on congruency effects, we correlated the mean luminance differences between black and white object cues and color targets with reaction times on a trial-by-trial basis. Similar to Experiment 1 we found a significant correlation in the imagery group ($r(1382) = .136$, $p < .001$) but not in the control group ($r(1275) = .003$. $p = .914$).

As in Experiment 1, we calculated the split-half correlation of the congruency effect in the experimental group. The results revealed a high reliability ($r(14) = .84$, p < .001). The mean VVIQ score was $M = 2.441$, $SD = .551$ in the experimental group and $M = 2.321$, $SD = .443$ in the control group. This difference was not significant ($t(29) = .669$, $p = .509$). Again we found no correlation between the individual congruency effect in the mental imagery group and the scores on the VVIQ, $r(14) = -.21$, $p = .44$) in the experimental group.

## Discussion

In Experiment 2, we investigated whether visualizing colors would influence reaction times in a color identification task while preventing participants to internally repeat the color verbally during the mental imagery period. As predicted, the mental imagery group was faster on congruent compared to incongruent trials, despite repeating a color-unrelated syllable (“ba”) during the color imagery period.

The replication of the congruency effect reported in Experiment 1 while the phonological loop was loaded with semantically task-unrelated information suggests that participants used a depictive representation to generate the colors during the imagery period Kosslyn (2005).

To demonstrate that color imagery functionally overlaps with color perception, as suggested by some of previous studies (Sparing, Mottaghy, Ganis, Thompson, Töpper, Kosslyn, et al., 2002; Thompson, Kosslyn, Sukel, & Alpert, 2001; for a review see Kosslyn & Thompson, 2003), one needs to provide evidence that the congruency effect found between imagery and perception is related to the congruency effect that occurs when color perception is cued with visually presented color. Experiment 3 was designed to provide such evidence.

## Experiment 3

In Experiment 3, participants were asked to perform two versions of the color task. In one version, participants were instructed to form a mental image of the cued color (mental imagery task) as in Experiments 1 and 2. In the other version, the cued color was visually presented in the square following the cue (perception task). If color imagery relies on a representation of the same format as color perception, then the congruency effects in these two tasks should be positively correlated.

### Methods

**Participants.** Thirty-two participants (16 females) ranging in age between 18 and 27 years ($M$ = 22.13, $SD$ = 1.9) were recruited. There was no compensation for participation in the study. All participants confirmed not to be color-blind. They all gave written informed consent to participate prior to the experiment and were treated in accordance with the ethical protocol approved by the Faculty of Human Sciences of the University of Bern and the "Ethical Principles of Psychologists and Code of Conduct" of the American Psychological Association (2002).

**Material.** The material was the same as in Experiments 1 and 2.

**Procedure.** Experiment 3 consisted of two tasks, an imagery task and a perception task. Task type was varied as a within-participant factor in counterbalanced order. The first half of the sample was assigned to the letter cue group, the second half to the object cue group. The imagery task was exactly the same as in Experiment 1 (mental imagery group).

The same material was used to create a perceptual color task, however with two changes. Unlike in the imagery task, the box was colored in the cued color in the perceptual task. After fixating for 500 ms and being cued for 500 ms, participants were presented with the cued color for 3000 ms. Then, a 200 ms blank was inserted before participants saw the target color until they gave a response. Since there were no effects of cue in Experiments 1 and 2, cue type was varied as a between-participant factor in Experiment 3 to shorten the procedure.

**Results**

As in Experiments 1 and 2, we excluded the first 10 trials of each task. Of all correct trials, we then excluded reaction times that deviated more than three standard deviations from each subject's mean (1.22% of the remaining trials). Errors occurred in less than 2% of the trials and did not differ as a function of condition. One participant was excluded from the data analysis because her reaction times deviated more than 2.5 SD from the mean of the group. Reaction times were analyzed using a mixed-design ANOVA with the within-participant factors task type (mental imagery vs. perception), congruency (congruent vs. incongruent) and the between-participant factor cue type (object vs. letters).

As shown in Figure 4 (see also Table 1), there was a significant effect of task type, $F(1, 29) = 11.55$, $p = .002$, $\eta_p^2 = .29$. Bonferroni corrected post-hoc comparisons revealed that participants were generally faster in the perception compared to the imagery task ($p = .002$). Also, there was a significant main effect of congruency, $F(1, 29) = 98.94$, $p < .001$, $\eta_p^2 = .77$. Bonferroni corrected post-hoc comparisons confirmed that participants were faster on congruent trials compared to incongruent trials ($p < .001$). As in the previous experiments, there was no effect of cue type, $F < 1$. None of the interactions reached significance (all *ps* > .35). The descriptive values of the accuracy data can be found in Table 2. The same mixed-design ANOVA on the accuracy did not reveal any main effects or interactions (all *p*s > .14). As in Experiments 1 and 2, we calculated the split-half reliability of the congruency effect. The results revealed a high correlation ($r(29) = .86$, $p < .001$).

As in Experiments 1 and 2, we correlated mean luminance differences between black and white object cues and color targets with reaction times on a trial-by-trial basis. These correlations were significant both in the imagery task ($r(1420) = .120, p < .001$) and in the perceptual task ($r(1422) = .103. p < .001$).

Correlational analyses revealed that the congruency effects in the mental imagery task correlated with the congruency effects in the perceptual task, $r(29) = .46, p = .01$ (see Figure 5). It could be argued that the relationship between the congruency effects in the mental imagery and perceptual task might be due to mean differences in overall reaction time. That is, the correlation could be explained by participants' individual response speed. We calculated a partial correlation between the congruency effects in the mental imagery task and in the perceptual task while controlling for individual differences in overall reaction time (i.e., mean reaction time across tasks and conditions). The partial correlation was significant, $pr(28) = .39, p = .03$. The mean VVIQ score was $M = 1.701$, $SD = .384$. As in the previous experiments, we found no relation between the congruency effects in the mental imagery task and the VVIQ scores, $r(29)= -.27, p = .15$.

**Discussion**

Experiment 3 provides direct evidence for a relationship between the congruency effects evoked by mental imagery and visual perception. Participants were faster on congruent compared to incongruent trials. This congruency effect was related to the reaction time difference in a perceptual version of the task. Reaction times were generally faster in the perceptual task compared to the imagery task. Most probably, this effect emerged due to the higher cognitive load in the imagery task. Together, these results suggest that color imagery functionally overlaps with color perception and are in line with previous findings demonstrating a modulatory influence of color imagery on subsequent perception (Chang et al., 2013).

## General Discussion

The goal of this study was to develop and validate an objective color imagery task while at the same time minimizing the influence of prior knowledge. Experiment 1 showed that the instruction to imagine colors influences reaction times in a subsequent color identification task. The reaction time difference between congruent and incongruent trials was larger in the group that was instructed to mentally visualize colors compared to the control group. In Experiment 2 we showed that this effect cannot be explained by verbal mechanisms. Participants who were instructed to imagine the colors showed a larger reaction time difference between congruent and incongruent trials than the control group, despite simultaneously performing an articulatory suppression task. Experiment 3 demonstrated that the congruency effect through mental color imagery is related to a perceptual congruency effect on an individual level. We found a congruency effect in all three independent samples and moreover, the reliability of the color imagery task was high in all experiments. Congruency-incongruency effects have been found frequently in cognitive science. Most notably, Stroop (1935) used color congruency in order to study attentional processes. While congruency-incongruency effects have already been used to investigate other forms of imagery such as motor imagery (e.g., Garbarini et al., 2014) or musical imagery (e.g., Yumoto et al., 2005), their application in color imagery research is novel. The findings of our three experiments suggest that this novel paradigm is apt to investigate color imagery abilities. In the following, we discuss implications of these results with regard to the format of representation that underlies mental imagery of colors, individual differences in color imagery abilities and implications for patients with a double dissociation between color imagery and color perception.

Our results speak for a pictorial representation format of mental imagery (Kosslyn, 2005). In Experiment 2, participants who were instructed to imagine the colors showed a larger reaction time difference between congruent and incongruent trials than the control group, despite performing an articulatory suppression task at the same time. This effect would not be expected if mental images were represented in a propositional format that functionally overlaps with linguistic processing. Moreover, in Experiment 3, the congruency effect evoked by mental color imagery was positively correlated with a perceptual congruency effect, even after correcting for the individual reaction time level.

Several studies have demonstrated that perception and imagery share common neural mechanisms. For example, the early visual cortex is involved in visual mental imagery (e.g., Kosslyn et al., 1995; Slotnick et al., 2005; for a review see Kosslyn & Thompson, 2003). Given that color imagery and color perception are functionally related (Experiment 3), it is likely that both rely on similar neuronal mechanisms, such as information processing in the color selective area V4. In fact, there is evidence that object color retrieval in a mental hue comparison task activates area V4 (Rich et al., 2006, but see Howard et al., 1998). Further evidence for shared neural mechanisms of imagery and perception is provided by Borst and Kosslyn (2008) who demonstrated that image scanning in spatial imagery structurally overlaps with perceptual image scanning. In a task requiring participants to decide whether an arrow points to one exemplar in a pattern of dots, participants' reaction times increased as the distance between the arrow and the target dot increased. Moreover, reaction times increased to the same degree when the dot pattern and the arrow were simultaneously presented or when the arrow was presented and the dot pattern had to be mentally visualized. Critically, the mental image scanning efficiency was related to the visual scanning efficiency suggesting a functional and structural overlap between mental imagery and visual perception. Consistent with these findings, reaction times in our experiment increased or decreased depending on congruency, no matter whether the colors were mentally visualized or perceptually present. Moreover, the congruency effects in the color imagery and the color perception task were correlated. Thus, the congruency effects in color imagery and color perception suggest that color imagery and color perception are functionally equivalent – that is, they share to some extent the same cognitive processes. Since we did not have a spatial dimension in our pure color stimuli, participants were not required to inspect their mental images (cf. Borst & Kosslyn, 2008). Nevertheless, generating a mental image of color and maintaining it until target onset (approximately 3s) was necessary for a congruency effect. Our paradigm does not allow distinguishing these two processes.

Color is defined by three dimensions: hue, luminance and saturation. Our results do not allow for separating color imagery along these dimensions. However, recently it has been demonstrated that participants are sensitive to luminance while mentally visualizing scenes as evidenced by pupillometry (Laeng & Sulutvedt, 2013). Thus, luminance might also have influenced our color imagery task. Indeed we found a relationship between object cue-target luminance differences and congruency effects in the imagery tasks in all three experiments as well as in the perceptual task in Experiment 3, while the control groups failed to show such effects. Crucially, cue luminance could not have influenced congruency effects in letter cue trials and the congruency effect did not depend on cue type. So, while luminance differences might influence mental color imagery to a certain extent, they are not mainly responsible for the effects found in the present study. In future studies it might be interesting to investigate whether luminance variations of the same hue produce different congruency effects.

If color imagery abilities are very fine tuned, one would expect larger congruency effects for trials in which the cue and target are more distant (e.g., “lemon” as cue when the target is bright yellow compared to “mustard” as cue). From the present study we are unable to determine whether and how individual differences in terms of what color is visualized when instructed to visualize, for example, “red” or “the color of a tomato”, influenced the congruency effects in our study. Thus, a systematic investigation of possible “distance effects” might shed light on this limitation.

Surprisingly, a small congruency effect even emerged when participants were not instructed to mentally visualize colors (control group, especially in Experiment 2). Most probably, semantic priming might account for these small effects. Alternatively, statistical learning might have played a role. In fact, although there was the same amount of congruent and incongruent trials, the probability of receiving a green target after a yellow-cue, for example, was smaller than for receiving a yellow target after the same cue. Nevertheless, this does not take away from our finding that the instruction to mentally visualize colors consistently resulted in a stronger congruency effect compared to the control groups.

A disadvantage of previous color imagery tasks used in clinical settings is that they can hardly account for individual differences. Consider a patient who fails to indicate whether the inside of a banana is brighter yellow than mustard or cannot judge whether it is true or false that carrots are purple. Color imagery deficits are not the only explanation that can account for failure in such tasks. Rather, the patient might fail to remember what the object actually is, the name of the color of the object, what color the object typically has and so on. Moreover, participants with the same accuracy in this task would misleadingly be categorized as having equal mental color imagery abilities. However, this does not mean that both participants imagined the colors with the same vividness.

Individual differences in mental imagery abilities are commonly assessed by using the VVIQ. Although this questionnaire has a remarkable reliability (McKelvie, 1995), the scores often fail to correlate with performance in experimental tasks. Indeed, it has been demonstrated that the VVIQ is not related to trial-by-trial ratings of vividness in imagery tasks (D'Angiulli, Runge, Faulkner, Zakizadeh, Chan, & Morcos, 2013; Laeng & Teodorescu, 2002; but see Pearson et al., 2011). One reason might be that the VVIQ taps into a set of mental imagery abilities, for example imagery of color, spatial position, shape, movement, odors and so on, whereas experimental imagery tasks capture isolated imagery components. Moreover, there could be individual variance between these imagery components. As such, one would expect a relationship between experimental and subjective measures of the same imagery component (e.g., color imagery), but no relationship between an experimental color imagery task and the set of different questions assessed by means of the VVIQ. Similarly, it has been demonstrated that an objective spatial imagery task is related to subjective measures of spatial imagery but not to the VVIQ and subjective measures of other imagery components such as objects (Borst & Kosslyn, 2010). Furthermore, previous studies report no or only weak relations between the VVIQ and spatial tasks (Danaher & Thoresen, 1972; Di Vesta, Ingersoll & Sunshine, 1971; Durndell & Wetherick, 1976a, 1976b; Ernest, 1977; Kosslyn, Brunn, Cave, & Wallach, 1984; Lorenz & Neisser, 1985; Paivio, 1971; Poltrock & Agnoli, 1986; Rehm, 1973; Richardson, 1977; Sheehan & Neisser, 1969). One could argue that our results are inconsistent with previous findings demonstrating a negative relationship between imagery vividness assessed by the VVIQ and color memory (Heuer, Fischman & Reisberg, 1986; Reisberg, Culver, Heuer & Fischman, 1986). However, several recent studies outside the color domain provide evidence for an overlap between short-term memory and mental imagery (Borst & Kosslyn, 2008; Borst, Niven, & Logie, 2012; Borst, Ganis, Thompson, & Kosslyn, 2012, Keogh & Pearson, 2011). It has to be considered that our task is neither a short-term nor a long-term memory task. Rather, it assesses the ability to imagine colors. Specifically, we argue that the congruency effects in our task emerged from interference between a mentally visualized and a visually perceived color.

Our paradigm might be of potential use in a clinical setting, given that the mental color imagery task we used in this study is highly reliable. Administering this task in patients reporting a color imagery deficit could shed light on the nature of their deficit. Assuming that this task reflects mental color imagery processes, patients showing no difference between congruent and incongruent trials in the color imagery task while performing well in mental hue comparisons are likely to have a true color imagery deficit. In contrast, patients who show a congruency effect in the mental color imagery task but who perform poorly on the conventional mental hue comparison test would be more likely to have an object-color knowledge deficit rather than a color imagery deficit. Thus, our mental color imagery task might be a promising tool to differentiate pure color imagery from color knowledge deficits.

A few points need to be taken into account when applying this paradigm to a patient population. First, in order to make sure that patients solve the task visually, it is recommended to conduct both the imagery and the perceptual task as well as an imagery condition with a simultaneous articulatory suppression task. Second, a condition in which patients or participants of future studies are not instructed to mentally visualize colors during presentation of the blank box might be helpful to control for priming effects (such as the task of the control group in the present experiments). Third, when applying this paradigm to a patient population one needs to ensure that participants understand the cues. For example, using object cues might not lead to the expected results when the patient suffers from an object memory deficit. Since cue type did not produce any differences in the congruency effects in any of our three experiments, even different cues that are also minimally suggestive could be used. Fourth, since the congruency effects in our tasks emerged due to interference between a mentally visualized and a visually perceived color, it might be worth to control for executive functions. Future studies might also adjust our paradigm in order to investigate form, orientation, motion, size, object or spatial imagery both in patients and in healthy participants.

Besides the potential clinical application of our paradigm, another domain in which color imagery might be of high interest is synesthesia research. Many forms of synesthesia involve sensations of colors when exposed to letters or digits, for example. Additional mental experiences such as these accompanying color sensations to graphemes raised the question whether synesthetes generally have more vivid imagery. Indeed, there is evidence supporting this hypothesis from subjective reports (Barnett & Newell, 2008; Price, 2009). Regarding the relationship between color imagery and synesthetic color experiences, Rich et al. (2006) found different brain activation for each of the two phenomena. However, considering that they used the mental hue comparison task to measure color imagery one might raise the same criticism as discussed above. Applying an experimental color imagery task in synesthesia research could further elucidate the functional and neuronal differences between synesthetes and controls in the visualization of colors.

To conclude, with the present study we suggest a novel, reliable approach to investigate visual mental color imagery abilities. We demonstrate that performance in this task cannot be attributed to verbal processes, but instead is related to performance in a perceptual version of the task.

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