

1 Running head: COLOR IMAGERY

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

9 Andrea L. Wantz^{1,2}, Grégoire Borst³, Fred W. Mast^{1,2}, Janek S. Lobmaier^{1,2}

10 ¹ Department of Psychology, University of Bern, Bern, Switzerland

11 ² Center for Cognition, Learning and Memory, University of Bern, Bern, Switzerland

12 ³ CNRS, Laboratory for the Psychology of Child Development and Education, Paris Descartes

13 University, Sorbonne, Paris, France

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24 Correspondence concerning this article should be addressed to Andrea L. Wantz,

25 University of Bern, Department of Psychology, Fabrikstrasse 8, CH-3012 Bern, Switzerland.

26 E-mail: andrea.wantz@psy.unibe.ch

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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

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Introduction

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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.

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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).

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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,

72 Ishai, Haxby, & Ungerleider, 2002, Kosslyn, Thompson, Kim, & Alpert, 1995; Slotnick,
73 Thompson, & Kosslyn, 2005; for a review see Kosslyn & Thompson, 2003). Indeed, the
74 results of neuroimaging studies with healthy participants on the degree of overlap of the brain
75 areas activated in color perception and color imagery remain largely inconclusive. Some
76 studies reported that object color retrieval elicits activation in the same areas as the ones
77 activated in color perception, notably in color selective visual areas such as V4 (Hsu,
78 Frankland, & Thompson-Schill, 2012; Hsu, Kraemer, Oliver, Schlichting, & Thompson-
79 Schill, 2011; Rich, Williams, Puce, Syngeniotis, Howard, McGlone, et al., 2006; Simmons,
80 Ramjee, Beauchamp, McRae, Martin, & Barsalou, 2007). Conversely, other neuroimaging
81 studies did not report a functional overlap between color imagery and perception (Bramao,
82 Faisca, Forkstam, Reis, & Petersson, 2010; Chao & Martin, 1999; Howard, Ffytche, Barnes,
83 McKeefry, Ha, Woodruff, et al., 1998; Lu, Xu, Jin, Mo, Zhang, & Zhang, 2010; Miceli,
84 Fouch, Capasso, Shelton, Tomaiuolo, & Caramazza, 2001).

85 A possible reason for the discrepancy in the literature might be the varying extent to
86 which the tasks used to measure the ability to visualize color did actually involve color
87 imagery. First, answering a question such as “what color is a lime?” might not rely
88 exclusively on the ability to generate an accurate visual mental image of a lime in color but
89 also on semantic knowledge about this object (i.e., color knowledge). Moreover, some color
90 terms are tightly linked to colors in a linguistic fashion (e.g., we refer to bright lucent green as
91 “lime green”). Some researchers have argued that both visual and/or verbal processes
92 contribute to color knowledge (Beauvois & Saillant, 1985) and that these processes might be
93 hard to distinguish in tasks in which participants need to determine the typical color of an
94 object (De Vreese, 1991). Second, mental hue comparison tasks such as “is a strawberry
95 darker red than a tomato?” can be solved with greyscale imagery. Third, the tasks designed to
96 date do not necessarily tap into pure color imagery but also involve the visualization of shape
97 and other attributes of the objects (Chang, Lewis, & Pearson, 2013). Last but not least, most

98 of these tasks are easy to solve, especially for participants with no color knowledge
99 impairments. Thus, the available tasks may not be subtle enough to assess individual color
100 imagery abilities of healthy participants.

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

109 The present study aimed at developing a refined pure color imagery paradigm. The
110 principle of this paradigm relies on the classical finding that visual mental imagery modulates
111 subsequent perception of visual stimuli (Chang, et al., 2013; Ishai & Sagi, 1995; Pearson,
112 Rademaker, & Tong, 2008; Perky, 1910). Participants were first instructed to visualize a color
113 in a blank box indicated either by the presentation of a greyscale picture of an object (i.e.,
114 lemon) or by the two first letters of the color to visualize. After the visualization period, a
115 color was displayed in that box. Participants were instructed to determine the visually
116 presented colors as fast and accurately as possible by pressing one of six keys. We expected
117 shorter reaction times on trials where the visualized color matched the presented color (i.e.,
118 congruent trials) when compared to trials where the visualized color did not match the
119 presented color (i.e., incongruent trials). In Experiment 1, we asked two groups of participants
120 to perform this task. One group was instructed to visualize the colors in response to the two
121 cue types (i.e., objects or first two letters of the color name). The other group received no
122 instruction to generate mental images of colors (control group). If color mental imagery
123 modulates reaction times in a subsequent color identification task then participants in the

124 mental imagery group but not in the control group should be faster to identify the color in
125 congruent trials than in incongruent trials. Experiment 2 was conducted in order to exclude
126 the possibility that the congruency effect reported in Experiment 1 (i.e., shorter response
127 times for congruent compared to incongruent trials) could be due to verbal priming. Finally,
128 in Experiment 3, we investigated whether individual differences in the congruency effects in
129 the mental imagery task were related to the congruency effects in a perceptual version of this
130 task (i.e., a color was displayed visually preceding the visual presentation of the color to
131 identify). We reasoned that if color imagery functionally overlaps with color perception, the
132 congruency effects in these two versions of the tasks should be correlated.

133 **Experiment 1**

134 **Methods**

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

143 **Material.** We designed two imagery cue types (letters, objects). In the letter condition,
144 we used the first two letters of the colors (e.g., “gr” for green) in 18 pt black Courier font on a
145 white background. Since a color word might automatically activate color concepts (as in the
146 classical Stroop task, Stroop, 1935), we presented only the first two letters of the cue word.
147 Because two color words used in the experiment start with the same letter in German (the
148 language in which the experiment was conducted), we presented not only the first but the first
149 two letters of the color words. The background was white (min luminance = 38.2 cd/m^2 , max

150 luminance = 41.4 cd/m², mean¹ = 255) throughout the experiment. In the object condition, six
151 standardized black and white objects from the bank of standardized stimuli (BOSS; Brodeur,
152 Dionne-Dostie, Montreuil & Lepage, 2010) were used, which were explicitly related to one of
153 the six visually presented colors (lemon (min luminance = 5.41 cd/m², max luminance = 20.4
154 cd/m², mean = 134.10), orange (min luminance = 3.82 cd/m², max luminance = 11.38 cd/m²,
155 mean = 112.77), tomato (min luminance = 2.3 cd/m², max luminance = 10.4 cd/m², mean =
156 72.93), eggplant (min luminance = 0.55 cd/m², max luminance = 5.69 cd/m², mean = 40.33),
157 lettuce (min luminance = 1.25 cd/m², max luminance = 16.9, mean = 89.92), walnut (min
158 luminance = 2.62 cd/m², max luminance = 7.40 cd/m², mean = 88.64)). It is possible that
159 black and white object images automatically activate color concepts because they are
160 concrete. Thus, we also included letter cues, which are less likely to trigger automatic
161 processes and conceptual biases. Using both types of cues allows for comparing possible
162 influences of automatic concept activation. Participants visualized one of six colors (yellow,
163 orange, red, purple, green, brown) in response to the letters or object cues within a blank
164 square. After participants visualized one of the six colors in the blank box, a colored square of
165 the same size was presented visually. We chose the following six colors (and corresponding
166 RGB and luminance values): yellow (255, 251, 0; min luminance = 33.9 cd/m², max
167 luminance = 36.3 cd/m², mean = 225), orange (230, 150, 0; min luminance = 20.3 cd/m², max
168 luminance = 21.9 cd/m², mean = 158), red (255, 37, 0; min luminance = 10.8 cd/m², max
169 luminance = 11.6 cd/m², mean = 98), purple (70, 30, 90; min luminance = 1.46 cd/m², max
170 luminance = 1.59 cd/m², mean = 49), green (1, 128, 0; min luminance = 9.07 cd/m², max
171 luminance = 9.54 cd/m², mean = 76) and brown (139, 69, 19; min luminance = 5.23 cd/m²,
172 max luminance = 5.47 cd/m², mean = 84). The viewing angle of the greyscale pictures of
173 objects, the blank square and the colored squares was approximately 10.7°.

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

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

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

196 Importantly, congruent trials were defined as trials in which the cued color and the
197 color presented visually matched (e.g., tomato-red). In incongruent trials, the cued and
198 displayed color did not match (e.g., lemon-purple). In each block, the same amount of
199 congruent and incongruent trials (50 trials each) appeared in randomized order. Participants

200 were randomly assigned to either the mental imagery or the control group and to one of two
201 task sequence conditions (object cues first, letter cues first). Reaction times (i.e., time
202 between the onset of the color square and the button-press) and accuracy were recorded. In
203 order to compare the results of our color imagery task with standard measures of general
204 visual imagery vividness and to control for group differences in standard imagery tests, all
205 participants completed a computer-based version of the vividness of visual imagery
206 questionnaire (VVIQ; Cui, Jeter, Yang, Montague & Eagleman, 2007; Marks, 1973) after the
207 color identification task.

208 **Results**

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

217 The descriptive data of the reaction times can be found in Table 1 and are depicted in
218 Figure 2. Whereas neither the cue type, $F < 1$, nor the group, $F(1, 30) = 1.87, p = .18$, had an
219 effect on reaction times, there was a significant main effect of congruency, $F(1, 30) = 25.04, p$
220 $< .001, \eta_p^2 = .46$). Bonferroni corrected post-hoc comparisons confirmed that participants
221 were generally faster on congruent compared to incongruent trials ($p < .001$). As expected, the
222 effect of the congruency varied in the two groups as revealed by a significant congruency
223 group interaction, $F(1, 30) = 9.02, p < .005, \eta_p^2 = .23$. Paired samples t-tests revealed that the
224 experimental group was significantly faster on congruent compared to incongruent trials
225 ($t(15) = -4.94, p < .001, d = 1.24$) whereas the control group did not show such an effect

226 ($t(15) = -1.71, p = .108$). No other two- or three-way interactions reached significance (all p s
227 $> .18$). A similar three-way mixed-design ANOVA on the accuracy data revealed no
228 significant main effects or interactions (all p s $> .062$, see Table 2 for mean accuracy)
229 suggesting that the reaction times cannot be explained by a speed-accuracy tradeoff.

230 One could speculate that the congruency effect in the object cue trials reflects
231 luminance congruency between cues and targets rather than effects of color imagery. If this
232 were the case, the same congruency effect would emerge even when participants simply
233 visualize the black and white object cue. To test this hypothesis, we correlated mean
234 luminance differences between object cues and color targets and reaction times on a trial-by-
235 trial basis. Indeed, there was a significant correlation in the imagery group ($r(1369) = .086, p$
236 $= .001$), however, this relationship was absent in the control group ($r(1383) = .021, p = .438$).

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

246 **Discussion**

247 Consistent with our hypotheses, we showed that visualizing colors influences
248 subsequent color identification reaction times. The reaction time difference between
249 congruent and incongruent trials was larger in the group that was instructed to mentally
250 visualize colors than in the control group. Moreover, the reliability of the color imagery task

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

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

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

288 **Results**

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

298 As shown in Figure 3 (see also Table 1), there was no effect of the cue type, $F(1, 28) =$
299 $2.456, p = .128$, or the group, $F < 1$. However, there was a main effect of congruency, $F(1,$
300 $28) = 65.991, p < .001, \eta_p^2 = .70$. Bonferroni corrected post-hoc comparisons revealed that
301 participants were significantly faster on congruent compared to incongruent trials ($p < .001$).
302 A significant two-way interaction, $F(1, 28) = 8.476, p = .007, \eta_p^2 = .23$ shows that the

303 congruency effect was larger in the mental imagery than the control group. There were no
304 other significant two-way or three-way interactions (all $ps > .305$). A similar three-way
305 ANOVA on the accuracy rate revealed no main effects or interactions (all $ps > 0.78$, see
306 Table 2), suggesting that no speed-accuracy tradeoff could account for the effect reported on
307 the reaction times.

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

313 As in Experiment 1, we calculated the split-half correlation of the congruency effect in
314 the experimental group. The results revealed a high reliability ($r(14) = .84, p < .001$). The
315 mean VVIQ score was $M = 2.441, SD = .551$ in the experimental group and $M = 2.321, SD =$
316 $.443$ in the control group. This difference was not significant ($t(29) = .669, p = .509$). Again
317 we found no correlation between the individual congruency effect in the mental imagery
318 group and the scores on the VVIQ, $r(14) = -.21, p = .44$) in the experimental group.

319 Discussion

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

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

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

335 **Experiment 3**

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

342 **Methods**

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

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

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

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

361 **Results**

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

370 As shown in Figure 4 (see also Table 1), there was a significant effect of task type,
371 $F(1, 29) = 11.55, p = .002, \eta_p^2 = .29$. Bonferroni corrected post-hoc comparisons revealed
372 that participants were generally faster in the perception compared to the imagery task ($p =$
373 $.002$). Also, there was a significant main effect of congruency, $F(1, 29) = 98.94, p < .001, \eta$
374 $_p^2 = .77$. Bonferroni corrected post-hoc comparisons confirmed that participants were faster on
375 congruent trials compared to incongruent trials ($p < .001$). As in the previous experiments,
376 there was no effect of cue type, $F < 1$. None of the interactions reached significance (all $ps >$
377 $.35$). The descriptive values of the accuracy data can be found in Table 2. The same mixed-
378 design ANOVA on the accuracy did not reveal any main effects or interactions (all $ps > .14$).
379 As in Experiments 1 and 2, we calculated the split-half reliability of the congruency effect.
380 The results revealed a high correlation ($r(29) = .86, p < .001$).

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

385 Correlational analyses revealed that the congruency effects in the mental imagery task
386 correlated with the congruency effects in the perceptual task, $r(29) = .46, p = .01$ (see Figure
387 5). It could be argued that the relationship between the congruency effects in the mental
388 imagery and perceptual task might be due to mean differences in overall reaction time. That
389 is, the correlation could be explained by participants' individual response speed. We
390 calculated a partial correlation between the congruency effects in the mental imagery task and
391 in the perceptual task while controlling for individual differences in overall reaction time (i.e.,
392 mean reaction time across tasks and conditions). The partial correlation was significant,
393 $pr(28) = .39, p = .03$. The mean VVIQ score was $M = 1.701, SD = .384$. As in the previous
394 experiments, we found no relation between the congruency effects in the mental imagery task
395 and the VVIQ scores, $r(29) = -.27, p = .15$.

396 **Discussion**

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

406 **General Discussion**

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

429 Our results speak for a pictorial representation format of mental imagery (Kosslyn,
430 2005). In Experiment 2, participants who were instructed to imagine the colors showed a
431 larger reaction time difference between congruent and incongruent trials than the control
432 group, despite performing an articulatory suppression task at the same time. This effect would

433 not be expected if mental images were represented in a propositional format that functionally
434 overlaps with linguistic processing. Moreover, in Experiment 3, the congruency effect evoked
435 by mental color imagery was positively correlated with a perceptual congruency effect, even
436 after correcting for the individual reaction time level.

437 Several studies have demonstrated that perception and imagery share common neural
438 mechanisms. For example, the early visual cortex is involved in visual mental imagery (e.g.,
439 Kosslyn et al., 1995; Slotnick et al., 2005; for a review see Kosslyn & Thompson, 2003).
440 Given that color imagery and color perception are functionally related (Experiment 3), it is
441 likely that both rely on similar neuronal mechanisms, such as information processing in the
442 color selective area V4. In fact, there is evidence that object color retrieval in a mental hue
443 comparison task activates area V4 (Rich et al., 2006, but see Howard et al., 1998). Further
444 evidence for shared neural mechanisms of imagery and perception is provided by Borst and
445 Kosslyn (2008) who demonstrated that image scanning in spatial imagery structurally
446 overlaps with perceptual image scanning. In a task requiring participants to decide whether an
447 arrow points to one exemplar in a pattern of dots, participants' reaction times increased as the
448 distance between the arrow and the target dot increased. Moreover, reaction times increased
449 to the same degree when the dot pattern and the arrow were simultaneously presented or when
450 the arrow was presented and the dot pattern had to be mentally visualized. Critically, the
451 mental image scanning efficiency was related to the visual scanning efficiency suggesting a
452 functional and structural overlap between mental imagery and visual perception. Consistent
453 with these findings, reaction times in our experiment increased or decreased depending on
454 congruency, no matter whether the colors were mentally visualized or perceptually present.
455 Moreover, the congruency effects in the color imagery and the color perception task were
456 correlated. Thus, the congruency effects in color imagery and color perception suggest that
457 color imagery and color perception are functionally equivalent – that is, they share to some
458 extent the same cognitive processes. Since we did not have a spatial dimension in our pure

459 color stimuli, participants were not required to inspect their mental images (cf. Borst &
460 Kosslyn, 2008). Nevertheless, generating a mental image of color and maintaining it until
461 target onset (approximately 3s) was necessary for a congruency effect. Our paradigm does not
462 allow distinguishing these two processes.

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

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

482 Surprisingly, a small congruency effect even emerged when participants were not
483 instructed to mentally visualize colors (control group, especially in Experiment 2). Most
484 probably, semantic priming might account for these small effects. Alternatively, statistical

485 learning might have played a role. In fact, although there was the same amount of congruent
486 and incongruent trials, the probability of receiving a green target after a yellow-cue, for
487 example, was smaller than for receiving a yellow target after the same cue. Nevertheless, this
488 does not take away from our finding that the instruction to mentally visualize colors
489 consistently resulted in a stronger congruency effect compared to the control groups.

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

499 Individual differences in mental imagery abilities are commonly assessed by using the
500 VVIQ. Although this questionnaire has a remarkable reliability (McKelvie, 1995), the scores
501 often fail to correlate with performance in experimental tasks. Indeed, it has been
502 demonstrated that the VVIQ is not related to trial-by-trial ratings of vividness in imagery
503 tasks (D'Angiulli, Runge, Faulkner, Zakizadeh, Chan, & Morcos, 2013; Laeng & Teodorescu,
504 2002; but see Pearson et al., 2011). One reason might be that the VVIQ taps into a set of
505 mental imagery abilities, for example imagery of color, spatial position, shape, movement,
506 odors and so on, whereas experimental imagery tasks capture isolated imagery components.
507 Moreover, there could be individual variance between these imagery components. As such,
508 one would expect a relationship between experimental and subjective measures of the same
509 imagery component (e.g., color imagery), but no relationship between an experimental color
510 imagery task and the set of different questions assessed by means of the VVIQ. Similarly, it

511 has been demonstrated that an objective spatial imagery task is related to subjective measures
512 of spatial imagery but not to the VVIQ and subjective measures of other imagery components
513 such as objects (Borst & Kosslyn, 2010). Furthermore, previous studies report no or only
514 weak relations between the VVIQ and spatial tasks (Danaher & Thoresen, 1972; Di Vesta,
515 Ingersoll & Sunshine, 1971; Durndell & Wetherick, 1976a, 1976b; Ernest, 1977; Kosslyn,
516 Brunn, Cave, & Wallach, 1984; Lorenz & Neisser, 1985; Paivio, 1971; Poltrock & Agnoli,
517 1986; Rehm, 1973; Richardson, 1977; Sheehan & Neisser, 1969). One could argue that our
518 results are inconsistent with previous findings demonstrating a negative relationship between
519 imagery vividness assessed by the VVIQ and color memory (Heuer, Fischman & Reisberg,
520 1986; Reisberg, Culver, Heuer & Fischman, 1986). However, several recent studies outside
521 the color domain provide evidence for an overlap between short-term memory and mental
522 imagery (Borst & Kosslyn, 2008; Borst, Niven, & Logie, 2012; Borst, Ganis, Thompson, &
523 Kosslyn, 2012, Keogh & Pearson, 2011). It has to be considered that our task is neither a
524 short-term nor a long-term memory task. Rather, it assesses the ability to imagine colors.
525 Specifically, we argue that the congruency effects in our task emerged from interference
526 between a mentally visualized and a visually perceived color.

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

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

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

563 research could further elucidate the functional and neuronal differences between synesthetes
564 and controls in the visualization of colors.

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

569 **Acknowledgments**

570 We would like to thank all participants who volunteered to take part in the study,
571 Sarah di Pietro and Silja Signer for helping with the data collection, and Stephen Kosslyn for
572 helpful advice. JSL was supported by grants from the Swiss National Science Foundation
573 (grant numbers PZ00P1_121622/1 and PP00P1_139072/1). This project was also supported
574 by the Center for Cognition, Learning and Memory of the University of Bern.

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