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# **Effects of background and contour luminance on the hue and brightness of the Watercolor effect**

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21 **Abstract**

22  
23 Conjoint measurement was used to investigate the joint influences of the  
24 luminance of the background and the inner contour on hue- and brightness filling-  
25 in for a stimulus configuration generating a water-color effect (WCE), i.e., a  
26 wiggly bi-chromatic contour enclosing a region with the lower luminance  
27 component on the exterior. Two stimuli with the background and inner contour  
28 luminances covarying independently were successively presented, and in separate  
29 experiments, the observer judged which member of the pair's interior regions  
30 contained a stronger hue or was brighter. Braided-contour control stimuli that  
31 generated little or no perceptual filling-in were also used to assess whether  
32 observers were judging the interior regions and not the contours themselves.  
33 Three nested models of the contributions of the background and inner contour to  
34 the judgments were fit to the data by maximum likelihood and evaluated by  
35 likelihood ratio tests. Both stimulus components contributed to both the hue and  
36 brightness of the interior region with increasing luminance of the inner contour  
37 generating an assimilative filling-in for the hue judgments but a contrast effect for  
38 the brightness judgments. Control analyses showed negligible effects for the  
39 order of the luminance of the background or inner contour on the judgments. An  
40 additive contribution of both components was rejected in favor of a saturated  
41 model in which the responses depended on the levels of both stimulus  
42 components. For the hue judgments, increased background luminance led to

43 greater hue filling-in at higher luminances of the interior contour. For the  
44 brightness judgments, the higher background luminance generated less brightness  
45 filling-in at higher luminances of the interior contour. The results indicate  
46 different effects of the inner contour and background on the induction of the  
47 brightness and coloration percepts of the WCE, suggesting that they are mediated  
48 by different mechanisms.

49

50

51 Keywords: filling-in, color assimilation, watercolor effect, color appearance,  
52 scaling, conjoint measurement, MLCM.

53 **1. Introduction.**

54 Color appearance is not determined only by the local light signals from each  
55 object but is also influenced by global contextual features. The watercolor  
56 effect (WCE) is an interesting phenomenon for studying such processes (Pinna,  
57 1987; Pinna et al., 2001). A pair of wiggly contours composed of a light  
58 chromatic contour (e.g., orange) surrounded by a darker chromatic contour (e.g.,  
59 purple) bounding an achromatic surface area elicits a filling-in of the hue of the  
60 lighter contour over the entire enclosed area (Figure 1a). The WCE is  
61 distinguished from other assimilation illusions by its large spatial extent; the  
62 phenomenon has been observed over distances of up to 45 deg (Pinna et al.,  
63 2001). In addition to the assimilative color spreading, the subjectively colored  
64 area is perceived as figure while the surrounding area appears as ground (Pinna  
65 et al., 2003; Pinna & Tanca, 2008; Tanca & Pinna, 2008).

66

67 **Figure 1 about here**

68

69 Studies of the WCE have typically examined the effects of the inducer  
70 configuration producing the WCE. For example, the intensity of the filling-in  
71 percept appears greater with increases in luminance contrast between the inner  
72 and outer contours for an achromatic WCE (Cao et al., 2011) and for a WCE  
73 that has both luminance and chromatic components (Devinck et al., 2005;  
74 Devinck & Knoblauch, 2012). Devinck et al. (2005) noted that observers did

75 not need to modify significantly the luminance of the enclosed area in a  
76 matching experiment. Other critical characteristics of the inducing contours that  
77 modulate the strength of the WCE include the continuity and contiguity of the  
78 contour pairs (Devinck & Spillmann, 2009; Devinck & Knoblauch, 2012).  
79 Recent demonstrations of the sensitivity of the phenomenon to contour  
80 adaptation provide additional support for a role of contour integration  
81 mechanisms in the WCE (Coia & Crognale, 2017). The strength of the  
82 phenomenon was found to be size-tuned with the strongest WCE observed for a  
83 contour width of about 15 arcmin and was optimal for equal contour widths  
84 (Devinck et al., 2014a). While the WCE has been reported for linear contours  
85 (Pinna et al., 2001), its strength is nearly independent of the amplitude of  
86 contour undulation but increases with contour frequency up to an asymptotic  
87 level (Gerardin et al., 2014). Finally, Pinna et al. (2001) demonstrated that  
88 several different color pairs can generate the coloration effect (see also Devinck  
89 et al., 2005). Specifically, Devinck et al. (2006) demonstrated that the  
90 coloration effect is stronger when the chromatic contrast is larger. Thus, the  
91 coloration effect depends on a conjunction of chromatic and luminance contrasts  
92 but also on spatial parameters of the inner and outer contours.

93 The WCE is perceptually salient but has proved difficult to quantify with  
94 precision showing large variability within and across observers (Cao et al.,  
95 2011; Devinck et al., 2005; von der Heydt & Pierson, 2006). More recently, the  
96 WCE was quantified by using paired-comparison methods that have been

97 extended to estimate perceptual scales within a signal detection framework  
98 (Devinck & Knoblauch, 2012). Two such procedures are Maximum Likelihood  
99 Difference Scaling or MLDS (Maloney & Yang, 2003; Knoblauch & Maloney,  
100 2008, 2012) and Maximum Likelihood Conjoint Measurement or MLCM (Ho et  
101 al., 2008; Knoblauch & Maloney, 2012). Difference scaling is useful for  
102 measuring perceptual strength along a single physical dimension, whereas  
103 conjoint measurement was conceived to assess the combined effects of several  
104 dimensions on appearance (Falmagne, 1985 ; Knoblauch & Maloney, 2012 ;  
105 Krantz et al., 1971; Luce & Tukey, 1964; Roberts, 1979). MLCM has been  
106 successfully applied to estimate perceptual scales associated with different sets  
107 of physical continua including surface material properties (Ho, Landy &  
108 Maloney, 2008; Qi, Chantler, Siebert & Dong, 2015; Hansmann-Roth &  
109 Mamassian, 2017), color appearance (Gerardin et al., 2014; Rogers, Knoblauch  
110 & Franklin, 2016) and time perception (Lisi & Gorea, 2016). The signal  
111 detection decision model allows specifying the perceptual scales in terms of the  
112 signal detection parameter  $d'$  (Gerardin et al., 2014; Knoblauch & Maloney,  
113 2012).

114 The aim of the present study is to estimate perceptual scales for two  
115 dimensions, the luminance elevation of the inner contour and the luminance  
116 elevation of the background. While the luminance contrast between the inner  
117 and outer contours has been tested intensively in the WCE, experiments  
118 evaluating the influence of the background luminance are scarce. Indeed, the

119 WCE has generally been demonstrated for a background of higher luminance  
120 than both inner and outer contours. Although the surround (e.g., the  
121 background) is known to be an important influence of color appearance  
122 (Brenner & Cornelissen, 2002 ; Brown & MacLeod, 1997 ; Shevell, 1978 ;  
123 Walraven, 1976), it has not been systematically explored for the coloration  
124 effect in the WCE. In addition, most studies of the WCE focus solely on its  
125 coloration effect. Here, we also investigate the influences of the background  
126 and inner contour luminances on the perceived brightness of the interior region.  
127 In summary, we employed conjoint measurement to study how both the  
128 background and the inner contour luminances influence judgments of both the  
129 hue and brightness in the WCE.

130

131

132

## 133 **2. General Methods**

### 134 *2.1. Observers*

135 Four observers participated in these experiments. Three were naïve and the  
136 fourth was one of the authors. Observers ranged in age between 26 and 40  
137 years. All had normal color vision as tested with the Farnsworth Panel D15, and  
138 had normal or corrected-to-normal visual acuity. Experiments were performed  
139 in accordance with the principles of the Declaration of Helsinki for the  
140 protection of human subjects.

141



## 142 2.2. Apparatus

143 Stimuli were presented on a NEC MultiSync FP2141sb color CRT monitor  
144 driven by a Cambridge Research ViSaGe graphic board with a color resolution  
145 of 14 bits per gun (Cambridge Research Systems, Rochester, United Kingdom).  
146 The experimental software was written to generate all stimuli, control stimulus  
147 presentation and collect responses in MATLAB 7.9 (MathWorks,  
148 <http://mathworks.com>), using the CRS Toolbox extensions. The monitor was  
149 calibrated using an OptiCal photometer with the calibration routines of  
150 Cambridge Research Systems. Observer position was stabilized by a chinrest and  
151 observer-to-screen distance was 80 cm. Experiments were performed in a dark  
152 room. Both eyes were used for viewing.

153

## 154 2.3. Stimuli

155 The stimuli were constructed as Fourier descriptors (Zahn & Roskies, 1972).  
156 Each stimulus was defined with respect to a circle of 3.2 deg diameter whose  
157 radius,  $r$ , was modulated sinusoidally as a function of angle according to the  
158 equation:

$$159 \quad R(\theta) = r + A\sin(2\pi f\theta) \quad (1)$$

160 where  $R$  is the stimulus radius at angle  $\theta$ ,  $r$  the average radius of the stimulus,  $A$   
161 the modulation and  $f$  the frequency in cycles per revolution (cpr). In the present  
162 study, the frequency was fixed at  $f = 10$  cpr and the amplitude of both contours  
163 at  $A = 0.36$  (Figure 1b, left).

164 All stimuli were composed of three colors: an orange inner contour ( $x,y =$   
165  $0.44, 0.43$ ) with the luminance varying from  $30.02 \text{ cd/m}^2$  to  $62.74 \text{ cd/m}^2$  and a  
166 purple outer contour ( $x,y = 0.31, 0.11$ ;  $Y = 21.12 \text{ cd/m}^2$ ), presented on a neutral  
167 white background ( $x,y = 0.29, 0.32$ ) with the luminance of the background (both  
168 outside and inside of the contours) varying between  $35.56 \text{ cd/m}^2$  and  $65.56$   
169  $\text{cd/m}^2$ . The contour pairs were each of width 16 arcmin, i.e., 8 arcmin for the  
170 inner and outer contours, each.

171 Stimuli were specified in the DKL color space (MacLeod & Boynton,  
172 1979; Krauskopf, Williams & Heeley, 1982; Derrington, Krauskopf & Lennie,  
173 1984). DKL color space is a three-dimensional opponent-modulation space  
174 based on the Smith and Pokorny (1975) cone fundamentals. The sum of L and  
175 M cone excitations varies on one axis (luminance), while M cone excitation  
176 subtracted from L cone excitation varies on the second axis ( $L - M$ ); and the sum  
177 of L and M cone excitations subtracted from S cone excitation varies on the  
178 third axis ( $S - (L + M)$ ). The DKL axes were scaled between -1 and 1, where +/-  
179 1 corresponds to the maximum contrast for each axis on the monitor. The  
180 stimuli were specified with the purple and orange contours at azimuth of 320  
181 and 45 deg respectively. Luminance of the independent variables is specified as  
182 elevation from the equiluminant plane. The luminance elevations of the orange  
183 contour in DKL color space varied from -0.6 to 0 while the luminance elevation  
184 of the background ranged from -0.5 to 0.

185 In the present study, five levels of luminance inner contour and five levels  
186 of luminance background were used. All levels were crossed creating a  $5 \times 5$   
187 grid with a total of 25 stimuli. Figure 2 shows an example of the range of  
188 stimuli used, with the inner contour luminance varying across rows and the  
189 background luminance across columns.

190

191 **Figure 2 about here**

192

193 Control stimuli were also tested consisting of patterns that were identical  
194 to the test stimuli except that the contours were interlaced (Figure 1b, right) and  
195 generated little filling-in, as previously demonstrated (Devinck & Knoblauch,  
196 2012; Devinck et al., 2014a; Gerardin et al., 2014). These control stimuli were  
197 used to verify that observers responded to the filling-in appearance and not to  
198 other stimulus features.

199

#### 200 *2.4. Procedure*

201 On each trial, two different stimuli chosen randomly from the  $5 \times 5$  grid were  
202 presented in succession to the observer. Observers performed two tasks in  
203 separate randomly ordered and counter-balanced sessions in which they  
204 compared the interior regions of the two successively presented stimuli. In the  
205 first task, observers were instructed to judge which central region evoked the  
206 strongest orange hue. In the second task, observers were asked to judge which

207 central region appeared brighter. An equal number of test and control stimuli  
208 were interleaved in each session. With 5 levels along each of the dimensions  
209 varied, there are  $(25 * 24)/2 = 300$  unordered pairs. Stimuli were randomly  
210 ordered for each presentation. On each trial, a randomly chosen pair of test or  
211 control stimuli was presented. A session consisted of the random presentation of  
212 all 600 test and control pairs. Each task was repeated five times, yielding 1500  
213 test and 1500 control trials for each observer.

214         Prior to the experiment, observers were dark-adapted for 3 min. At the  
215 beginning of each trial, a fixation cross was presented in the center of the screen  
216 of duration 500 ms. At its extinction, the first pattern was presented during 500  
217 ms followed by a fixation cross for 500 ms, and then the second pattern for 500  
218 ms., followed by a blank screen. The observer's response initiated a 1 s pause  
219 before the start of the next trial. An initial practice block of 10 trials preceded  
220 the experiment. The experimental session started, when the observer felt at ease  
221 with the task, otherwise additional practice sessions were run. A free viewing  
222 procedure was used to ensure that observer's judgments were based on foveal  
223 views of the stimuli.

224

## 225 *2.5. Model*

226 The data were analyzed as a decision process within the framework of a signal  
227 detection model and fit by maximum likelihood (Ho et al., 2008; Knoblauch &  
228 Maloney, 2012). Three nested models of the decision process are fit to obtain

229 the best prediction of the set of observers' choices: an independence model, an  
230 additive model and a saturated model. Each model yields estimates of  
231 perceptual scale values or internal responses that have the property that equal  
232 differences in response are perceptually equal. The independence model fits the  
233 observer's judgments based on only one of the component dimensions. The  
234 additive model fits the judgments based on the sum of component psychological  
235 responses generated by the physical dimensions. The saturated model fits the  
236 observer's judgments including an interaction term that depends on the specific  
237 levels of the two components in addition to their simple additive combination.  
238 The three models are then evaluated using a nested likelihood ratio test. This is  
239 done separately for the experiments based on hue, and brightness judgments.  
240 The formal description of the model is described next and follows similar  
241 descriptions elsewhere (Gerardin et al., 2014; Ho et al., 2008; Knoblauch &  
242 Maloney, 2012).

243 We represent the stimulus levels along the two dimensions by a variable  
244  $\phi_{i,j}$ , where  $i$  and  $j$  correspond to the luminance levels of the background and the  
245 inner contour, respectively. In the decision models, each of the dimensions  
246 contributes a response,  $\psi_i^1$ ,  $\psi_j^2$ , to the intensity of the perceived filling-in  
247 depending on the corresponding physical intensity levels, where the superscripts  
248 correspond to the responses to the background and interior contour luminances,  
249 respectively. In the additive model, when observers judge which central area is

250 the more saturated orange color or which appears to be brighter, we suppose that  
251 the filling-in response is the sum of the component responses

$$252 \quad \psi_{i,j} = \psi_i^1 + \psi_j^2. \quad (2)$$

253 Observers compare the two presented central surfaces and the difference  
254 between the filling-in strength of the stimulus  $\phi_{i,j}$  and the stimulus  $\phi_{k,l}$  is  
255 computed as follows

$$256 \quad \Delta(i, j, k, l) = (\psi_i^1 + \psi_j^2) - (\psi_k^1 + \psi_l^2) + \varepsilon \quad (3)$$

257 where  $\varepsilon$  refers to additive noise in the decision process and is modeled as a  
258 Gaussian random variable with  $\mu = 0$  and variance  $= \sigma^2$ . In plots, we indicate  
259 the stimulus level by the index and not by the physical units, allowing both  
260 dimensions to be plotted together. With 5 levels along each dimension, there are  
261  $2 * 5$  levels plus 1 variance = 11 parameters to estimate. To make the model  
262 identifiable, however, the response at the lowest level along each dimension is  
263 arbitrarily set to 0,  $\psi_1^1 = \psi_1^2 = 0$ , and the variance is fixed to 1 for each  
264 estimated value, yielding only 8 parameters to estimate. The parameter values,  
265  $\psi_i^j$  are chosen to maximize the likelihood,  $\mathcal{L}(\Psi; R)$ , over the ensemble of  
266 choices,  $R$ , made by the observer.

$$267 \quad \mathcal{L}(\Psi; R) = \prod_i \Phi\left(\frac{\Delta_i}{2}\right)^{R_i} \left(1 - \Phi\left(\frac{\Delta_i}{2}\right)\right)^{1-R_i}, \quad (4)$$

268 where  $\Phi$  is a cumulative distribution function for a Gaussian with mean 0 and  
269 variance 1. The 2 in the denominator of the argument scales the variance for  
270 each value of  $\psi$  to 1 so that the perceptual scale values are parameterized in

271 terms of  $d'$ . In practice, this is performed using a Generalized Linear Model  
272 with the **MLCM** package in R (Knoblauch & Maloney, 2012, 2014).

273 If the observer's judgments depend on only one of the component  
274 dimensions, we obtain the independence model, reducing the decision variable  
275 to

$$276 \quad \Delta(i, j, k, l) = \psi_i^1 - \psi_k^1 + \varepsilon \quad (5)$$

277 where the judgments depend on only dimension 1, here. In this reduced model,  
278 the values of  $\psi_j^2$  are fixed at 0 and there are only 4 free parameters to estimate.  
279 Replacing the superscript 1 by 2 yields the independence model for the other  
280 dimension.

281 Finally, the saturated observer model includes an interaction factor that  
282 depend on the intensity levels of both dimensions; the decision variable is  
283 defined as follows:

$$284 \quad \Delta(i, j, k, l) = (\psi_i^1 + \psi_j^2 + \psi_{ij}^{12}) - (\psi_k^1 + \psi_l^2 + \psi_{kl}^{12}) + \varepsilon \quad (6)$$

285 Due to the interaction terms, the responses cannot be explained by a simple  
286 additive combination of components as in the previous two models. With 5  
287 levels along each dimension, only one cell in the 5x5 grid of responses is fixed  
288 at 0 leading to 24 (the maximum) free parameters to estimate, which is the  
289 origin of the term saturated.

290 We analysed the data using the MLCM package (Knoblauch & Maloney,  
291 2012, 2014) in the open source software R (R Core Team, 2017) to estimate the

292 perceptual scale values and model the contribution of both dimensions. The  
293 likelihood ratio tests were evaluated using a  $\chi^2$  statistic with degrees of freedom  
294 the difference in number of parameters fit for each pair of models.

295

### 296 **3. Results**

297 Judgments based on color and on brightness from the observers are shown in  
298 Figure 3 for test and control conditions in Conjoint Proportion Plots or CPP (Ho  
299 et al., 2008 ; Knoblauch & Maloney, 2012). In the CPP, the raw data are  
300 presented in a grid format in which each cell of the grid corresponds to one  
301 stimulus pair comparison. Each CPP contains all stimulus combinations and  
302 summarizes the proportion of times the stimulus  $S_{kl}$  was judged for one response  
303 criterion, hue (a) or brightness (b), to show a greater filling-in than the stimulus  
304  $S_{ij}$ , coded according to the grey levels indicated by the color bar presented on the  
305 right side of each graph. The levels of both dimensions are represented along  
306 each axis where the 5×5 outer check indicates the stimulus levels along one  
307 dimension and with each outer check subdivided into smaller 5×5 checks  
308 indicating the stimulus levels for the second dimension. Figure 3c shows the  
309 expected pattern of responses for an ideal observer who chooses only the higher  
310 level along one of the two stimulus dimension. The CPP presented on the left  
311 side indicates the results when the judgments depend on the first dimension  
312 alone (here, the background luminance) and the CPP displayed on the right side



313 when the judgment depend on the second dimension (here, the inner contour  
314 luminance).

315 Results from the hue and brightness judgments for each observer are  
316 shown in Figure 3a and 3b respectively with the results displayed on the top row  
317 for the test condition and on the bottom row for the control condition in each  
318 figure. For the hue judgments, the CPP for the test stimuli resembles more  
319 closely the ideal CPP displayed for the second dimension, suggesting that the  
320 luminance of the inner contour contributed more strongly to the choices than the  
321 luminance of the background. For the brightness judgments, the CPP for the test  
322 stimuli is more similar to the ideal CPP displayed for the first dimension,  
323 indicating that the luminance of the background contributed more strongly to the  
324 choices in comparison with the luminance of the inner contour. Deviations from  
325 the ideal patterns, however, indicate contributions from both dimensions for  
326 both tasks.

327 In these experiments, observers were instructed to judge the appearance of  
328 the interior region of the stimulus. However, it is possible that observers  
329 attended to the experimental dimensions (e.g., the continuity of the color of the  
330 contour) instead of the appearance of the interior region. If this were the case,  
331 we should obtain the same pattern of responses between the test and the control  
332 conditions. However, the test CPP patterns are different, with the control CPP  
333 patterns showing little, if any, systematic structure.

334

335

### Figure 3 about here

336

337           Statistical comparisons of additive and independence models based on a  
338 nested likelihood ratio test are shown in Table I for judgments based on hue and  
339 in Table II for judgments based on brightness. In these tables, each row  
340 indicates the test for an observer, and the last column corresponds to the  
341 probability that the additive model fits no better than the independence model.  
342 The degrees of freedom are obtained from the difference of the number of  
343 coefficients estimates in each model (8 (additive) – 4 (independence) = 4).  
344 Comparing the independence with the additive model indicates that the  
345 independence model can be rejected for the test stimuli for both tasks and for all  
346 observers ( $p < 0.001$ ). The motivation for testing the nested decision models for  
347 the control stimuli is less clear. Instead, we used a linear mixed-effects model to  
348 test if the estimated perceptual scale values depended significantly on the  
349 stimulus level with a random observer intercept (Bates et al., 2015). For both  
350 the hue and the brightness judgments, no significant dependence was found  
351 (hue:  $\chi^2(30) = 38.5, p = 0.14$ ; brightness:  $\chi^2(30) = 22.2, p = 0.85$ ). It could  
352 be argued that 4 observers is not sufficient to estimate the variances accurately  
353 in a mixed-effect model. We also performed the tests using a linear model with  
354 Observer entering as a fixed-effect, with no significance obtained in either case.  
355 The advantage of the mixed-effects model is that the results generalize to the

356 population rather than just the sample of 4 observers tested (Knoblauch &  
357 Maloney, 2012; Moscatelli et al., 2013; Pinheiro & Bates, 2000).

358

359 **Tables I and II about here**

360

361 Figure 4 shows the estimated contributions of each dimension obtained  
362 from fitting the additive model for each of the tasks. For judgments based on  
363 hue, the average estimated scales for each pair of inner contour luminance and  
364 background luminance elevation are shown in Figure 4 (a) for 4 observers. In  
365 this figure, the column labels indicate the observer identification. The top row  
366 shows the scale values estimated for the test stimulus and the bottom for the  
367 control stimulus. Black circles indicate the inner contour contribution and white  
368 the background contribution to the judgments. The values on the abscissa  
369 indicate the five stimulus levels for each dimension coded from 1 to 5. These  
370 values are indices to the 5 luminance elevations of the inner contour and the  
371 background used in the experiment.

372 The results in Figure 4a indicate that the contribution of the luminance of  
373 the interior contour dimension to the hue filling-in strength of the inner contour  
374 as does the contribution of the background increases with luminance elevation  
375 but with a smaller effect. The second row shows results obtained for the control  
376 stimuli. Here, there appears no systematic influence of either dimension on the  
377 strength of the coloration effect, because both dimension contributions are close

378 to zero at all stimulus levels. This result further supports that the observers  
379 based their judgments on the perceived filled in color of the interior rather than  
380 the luminance of the inner contour or the background.

381

382 **Figure 4 about here**

383

384 Figure 4 (b) shows the average estimated scales for each observer for each  
385 pairing of inner contour and background luminance elevations when judgments  
386 were based on the brightness of the interior region. The information in the  
387 figure is organized in the same fashion as Figure 4a. The top row shows the  
388 additive model fits to judgments of the brightness of the interior region. As the  
389 inner contour increases in luminance, the estimated contribution for this  
390 component decreases, indicating that the brightness of the interior region  
391 decreases, i.e., generating a relative contrast rather than an assimilative effect.  
392 The background dimension contributes positively with the luminance elevation  
393 to judgments of brightness. These results contrast with the scales estimated for  
394 the control stimuli that show no difference and little effect of both dimensions  
395 on the strength of brightness filling-in.

396 Temporal forced choice experiments can be subject to order effects  
397 (Yeshurun et al., 2008). To test for this, we compared the scales obtained for  
398 trials in which the higher luminance was presented in the first interval with the  
399 trials in which it was presented in the second interval. We performed the same

400 analysis with respect to the luminance of the inner contour. For the hue  
401 judgments, the average estimated scales for each background luminance order  
402 are shown in Figure 5 (a) for 4 observers, and judgments based on brightness are  
403 displayed in Figure 5 (b). In these figures, the column labels indicate the  
404 observer identification. The top row shows the estimated scale values for the  
405 contribution of the inner contour luminance and the bottom for the background  
406 dimension. White circles indicate the dimension contribution to the judgments  
407 when the luminance elevation of the background is higher in the first stimulus  
408 presentation and black circles the contribution to the judgments when the  
409 luminance elevation of the background is higher in the second presentation. The  
410 values on the abscissa indicate the five levels of each dimension coded from 1 to  
411 5. For judgments based on hue, the results in Figure 5a indicate that the  
412 contribution of the inner contour dimension is not different between both  
413 background presentation orders. Moreover, the background dimension is  
414 approximately the same between the presentation orders. Similar results were  
415 obtained when judgments were based on brightness (Figure 5b). This shows  
416 that any order effect based on the luminance background is very slight or absent  
417 in our experiments.

418 For completeness, we show in Figure 6 the effect of the presentation order  
419 of the luminance of the inner contour on the estimated scales for both judgments  
420 organized in the same fashion as Figure 5. For both tasks, the scales for neither  
421 dimension were influenced as a function of the presentation order.

422

423

**Figure 5 and 6 about here**

424

425 Comparing the saturated and additive models with nested likelihood ratio

426 tests rejected the hypothesis that the saturated model provided a fit no better

427 then the additive model, thus, demonstrating that an interaction term is required

428 to describe the observers' judgments for both tasks (Tables III and IV). The

429 degrees of freedom indicate the difference of the number of coefficients

430 estimated in the 2 models (24 (saturated) – 8 (additive) = 16). The additive

431 model fit was rejected in all 8 tests. The estimated coefficients for the saturated

432 model are shown for each observer and both tasks in the panels of Figure 7. In

433 these displays, the estimated scale values are plotted as a function of the

434 stimulus index for the luminance of the inner contour with the index of the

435 background luminance specified as a parameter for each curve. The results for

436 the hue judgments are presented on the top row with the brightness judgments

437 on the bottom. The averages of the four observers for both judgment conditions

438 are summarized as three-dimensional surfaces in Figures 8a and b. If the

439 additive model was a good fit to the data, the curves for different background

440 levels would be parallel in Figure 7. However, for both the hue and brightness

441 responses, as the background luminance increases, the curves fan out. For the

442 hue judgments, this results in a larger range of hue responses to the range of

443 inner contour luminances tested for the higher than lower luminance

444 backgrounds. For the brightness judgments, in contrast, the range of response  
445 decreases at the highest luminance background. Thus, the background  
446 luminance produces different effects on both the type of filling-in (assimilation  
447 vs contrast) for hue and brightness judgments and on the dynamic range of the  
448 response, expanding it for hue judgments but compressing it for brightness.

449

450 **Figures 7 and 8 about here**

451

452 **Tables III and Table IV about here**

453

#### 454 **4. Discussion**

455 In the present study, MLCM was used to quantify the contributions to the  
456 filling-in strength of the WCE of two stimulus dimensions: the background and  
457 inner contour luminances. We quantified how changes in these features affected  
458 perceived filling-in using two separate response criteria, linked to the strength of  
459 the hue (the conventional WCE) and the brightness of the interior region.  
460 Control experiments using a stimulus contour that generated statistically  
461 undetectable filling-in confirmed that observers judged the perceived attributes  
462 of the interior regions and not changes in the background and contour  
463 luminances, per se. We also found that the results were largely independent of  
464 the ordering of presentation in a trial of both the backgrounds and the inner  
465 contours.

466 As found previously, the strength of the coloration effect depends on the  
467 luminance of the inner contour (Devinck & Knoblauch, 2012; Devinck et al.,  
468 2014; Gerardin et al., 2014). Here, we show that the stimulus configuration  
469 inducing the WCE generates both a hue and also a brightness filling-in of the  
470 interior area and that these two phenomena are differentially affected by the  
471 stimulus dimensions that we manipulated. The hue filling-in effect was  
472 assimilative, and the hue became more saturated with increases in luminance of  
473 the inner contour and the background. However, luminance of the interior  
474 contour generated a contrast effect for brightness, in that the judged brightness  
475 of the interior region decreased at higher contour luminances. As observers  
476 compared the interior regions of the two successively displayed stimuli and  
477 judged which central region appeared brighter, it is still possible that the  
478 perceived filling-in was assimilative, i.e., the same contrast polarity as the inner  
479 contour and that the effect of the contour luminance was simply to reduce the  
480 lightness. This is difficult to assess since we cannot simply compare the interior  
481 with the surround because both the surround and the interior vary in each  
482 condition. Additionally, if we hold the surround constant, then we cannot rule  
483 out its effect on the interior.

#### 484 **The hue effect**

485 Both the hue and the brightness of the interior region were judged to be  
486 greater with increases in the luminance elevation of the background. Pinna et al.  
487 (2001) have previously reported that color spreading in the WCE occurs not



488 only with a white background but also with grey backgrounds and that even a  
489 faint spreading is perceived with dark backgrounds. Our results agree with these  
490 observations in that the background contribution to the hue judgments increased  
491 at higher luminances.

492 We also found that hue filling-in was more pronounced for bright than  
493 dim backgrounds. Previous studies have reported that color saturation  
494 diminishes when the brightness contrast between a colored object and its  
495 luminance background increases, a phenomenon named the gamut expansion  
496 effect (Brown & McLeod, 1997) subsequently confirmed and quantified by  
497 several investigators (Bimler et al., 2009; Faul et al., 2008; Xing et al., 2015).  
498 In contrast with these studies, our experiment shows that increasing the  
499 background luminance strengthens the assimilation hue, suggesting that we are  
500 observing a different phenomenon.

### 501 **The brightness effect**

502 The WCE has typically been described as a coloration effect. Brightness  
503 variations in the interior region of the stimulus have not typically been  
504 systematically quantified. One exception to this concerns studies that used an  
505 achromatic stimulus configuration (Cao et al., 2011; Coia & Crognale, 2017).  
506 In Coia and Crognale (2017), observers compared the filling-in region in the  
507 WCE to a reference stimulus with a physical luminance difference. Their  
508 matching results indicated that the test field shifted in the opposite direction

509 from the inner contour showing an assimilation effect. In Cao et al. (2011), the  
510 luminances of the inner contour and the luminance of the background were fixed  
511 while the outer contour varied between high and low luminance levels, thus  
512 varying the contrast. Observers were asked to report which of two interior  
513 surface stimuli appeared darker. Their results followed a U-shape with the  
514 strength of the effect maximized for a range of medium luminance levels but not  
515 for the extreme luminance levels. Consequently, the luminance contrast  
516 between both contours affects the WCE but not linearly. An intriguing point is  
517 the authors' description of their results: "Although there is an apparent  
518 assimilation effect in the chromatic WCE, it is hard to tell whether it is actually  
519 assimilation or some type of contrast effect happening here for the 'opposite  
520 polarity' condition". As their method based the estimation of the WCE strength  
521 on the probability of discriminating which stimulus appeared darker, we can  
522 assume that if responses are inferior to 50%, then the surface appears lighter but  
523 not equal (which would be the case for responses equal to 50%), indicating a  
524 contrast rather than an assimilation effect. For our experiment based on  
525 brightness judgment, when the inner contour increases in luminance, the  
526 estimated contribution for this component decreases, indicating that the  
527 brightness of the interior region decreases, also indicating a contrast  
528 phenomenon. Thus, the two sets of results may be in agreement. Nevertheless,  
529 the nature of the brightness effect could be influenced by the presence of the  
530 chromatic component in our stimulus situation.

531 In Devinck et al. (2005), observers were allowed to adjust both the  
532 luminance and the chromaticity of a field in order to match the color of the  
533 WCE. The mean luminance match was near the luminance of the background,  
534 indicating that little or no luminance adjustment was required to make a  
535 perceptual match. The authors concluded that the WCE is predominantly a  
536 chromatic effect as originally suggested by Pinna et al. (2001). These results are  
537 not necessarily in conflict with the current study, in that we observed that the  
538 variation in brightness contrast with inner contour luminance is diminished at  
539 high backgrounds and might have been difficult to detect via matching. We  
540 would predict, then, that manipulating the luminance of the background would  
541 affect the luminance match, but this would require a more systematic study of  
542 the background than was performed by Devinck et al. (2005). Here, our data  
543 indicate that the perceptual effect is not limited only to a coloration phenomenon  
544 in that both the background and inner contour luminances influence observers'  
545 judgment of the brightness of the central surface. A simple hypothesis to  
546 account for the reduced brightness effect at high background luminances is to  
547 suppose that the background light added to the interior region cancels the  
548 contrast effect. This would not explain, however, the fact that higher  
549 background luminances led to a stronger hue percept.

550

551

552

553 **Assimilation vs contrast**

554 Whether one observes a contrast or assimilation effect may depend on the width  
555 of the contours (Fach & Sharpe 1986 ; Helson & Rohles, 1959; Helson, 1963).  
556 Other factors such as the luminance of the inducing stimuli can also influence  
557 our percept. Thus, de Weert and Spillmann (1995) indicated that assimilation or  
558 contrast occurred depending on whether the inducing contours of varied  
559 reflectance were darker or lighter than the gray background in using a  
560 pincushion pattern. A matching experiment for brightness judgements indicated  
561 that contrast occurred when the luminance level of the inducing contour was  
562 above the luminance level of the background and that assimilation occurred  
563 when the luminance of the inducing contour was below the luminance of the  
564 background. Given the different spatial dependencies of chromatic and  
565 luminance sensitive mechanisms, one might expect differences in the spatial  
566 domains over which chromatic and luminance components of a stimulus induce  
567 assimilation and contrast. Given the dependence of induction phenomena on  
568 stimulus configuration, however, (Fach & Sharpe 1986; de Weert & Spillmann  
569 1995; Smith et al. 2001; Monnier & Shevell 2003, 2004), it is difficult to predict  
570 *a priori* whether the dimensions of the contours that we used should predict one  
571 or the other for the hue and brightness judgments.

572 In our study, observers compared the interior regions of the two  
573 successively displayed stimuli and judged which central region appeared  
574 brighter. Under this condition, our results indicated that the brightness of the

575 interior region decreases generating a relative contrast rather an assimilation  
576 effect. However, it still possible that different visual phenomena are perceived  
577 in other circumstances. In making a brightness judgements of the central region  
578 with respect to the outer region, we noted an assimilation phenomenon at the  
579 lowest luminance level of the background and at the highest luminance level of  
580 the inner contour. This condition corresponds to the lower left corner in Figure  
581 2.

### 582 **Unitary vs multiple mechanisms**

583 The color of the central surface in the WCE is characterized by a spread  
584 of color from the inner contour. Most previous studies of the WCE reported that  
585 the coloration effect depends on both the chromatic and luminance contrasts of  
586 the inner and outer contours. For example, most authors demonstrated that the  
587 coloration effect increases with increasing luminance contrast between inner and  
588 outer contours (Devinck & Knoblauch, 2012; Devinck et al., 2005).  
589 Additionally, the coloration effect increases when the chromatic coordinates of  
590 the inner and outer contours are approximately complementary in the color  
591 diagram (Devinck et al., 2006). Thus, the main explanation assumes a filling-in  
592 process in which a neuronal mechanism detects the contour and generalizes it  
593 beyond the confines of the immediate stimulus. Most studies in the WCE have  
594 reported an important role for several types of contour mechanisms generating a  
595 long-range filling-in percept. Taken together, these data suggest that the filling-  
596 in process involved in the WCE requires multiple levels of processing (Devinck

597 et al., 2014b; Pinna et al., 2001; Pinna & Grossberg, 2005; von der Heydt &  
598 Pierson, 2006). The present results indicate that the mechanisms inducing the  
599 brightness and coloration percept in the WCE are affected differently by the  
600 luminance of the inner contour. These opposing responses due to the inner  
601 contour suggest that multiple mechanisms contribute to the appearance of the  
602 interior region. Different mechanisms could be activated or inhibited yielding to  
603 color assimilation or brightness contrast effects, respectively. Future  
604 experiments based on visual masking or contour adaptation could investigate  
605 such phenomena.

606

607

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609

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612

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## 732 **Figure Legends**

733 Fig. 1: (a) Example of the Watercolor Effect. When a light orange contour is  
734 surrounded by a dark purple contour, the enclosed area takes the tint of  
735 the orange border. (b) Example of stimuli using Fourier descriptor as  
736 test stimulus (presented on the left side) and using braided contour as  
737 control stimulus (displayed on the right side).

738  
739 Fig. 2: Examples of stimulus set used for a conjoint measurement experiment.  
740 The figure indicates the set of stimuli used in both judgment tasks.  
741 Each column corresponds to a different luminance elevation of the  
742 background and each row to a different luminance elevation of the  
743 inner orange contour.

744  
745 Fig. 3: Conjoint proportion plots for judgments based on hue (a) and on  
746 brightness (b). Each plot shows the proportion of stimulus  $S_{kl}$  judged to  
747 have a greater filling-in than the stimulus represented in abscissa  $S_{ij}$  as  
748 grey level according to the color bar on the right side. The luminance  
749 elevation of the background is indicated by the large grids  $(i,k)$  and  
750 each grid is subdivided into smaller 5×5 grid indicating the luminance  
751 elevation of the inner contour  $(j,l)$ . In each set of graphs, the top row  
752 indicates the results for the test stimuli and the bottom for the control

753 stimuli for 4 observers. (c) Conjoint proportion plots for a simulated  
754 observer. Expected responses for an observer who judges the stimuli  
755 based on the contributions along only one of the dimensions.

756

757 Fig. 4: (a) Estimated scales for judgments based on hue. Additive model  
758 average estimates for test (top row) and control stimuli (bottom row) as  
759 a function of inner contour elevation (black circles) and luminance  
760 background elevation (white circles) for four observers. Error bars  
761 show 95% confidence intervals for estimates across the 5 runs. (b)  
762 Results for judgments based on brightness. The solid lines indicate the  
763 estimated contributions of each dimension under the additive model for  
764 test (top row) and control patterns (bottom row) as a function of inner  
765 contour elevation (black circles) and luminance background elevation  
766 (white circles) for four observers. Error bars show 95% confidence  
767 intervals for estimates across the 5 runs.

768

769 Fig. 5: (a) Results for judgments based on hue depending on the presentation  
770 order for the luminance background of the test stimulus. The solid  
771 lines indicate the estimated contributions under the additive model for  
772 the inner contour dimension (top row) and the background dimension  
773 (bottom row) as a function of the background order presentation. The  
774 white circles are used to indicate that the luminance elevation of the

775 background is higher in the first interval than in the second interval and  
776 the black circles are used to represent a higher luminance elevation of  
777 the background in the second interval than in the first interval. Error  
778 bars are 95% confidence intervals based on a bootstrap procedure  
779 (Knoblauch & Maloney, 2012). (b) Results for judgments based on  
780 brightness depending of the luminance background presentation order  
781 for the test stimulus. Additive model average estimates for the inner  
782 contour dimension (top row) and the background dimension (bottom  
783 row) when the luminance elevation of the background is higher in the  
784 first interval than in the second interval (white circles) and when the  
785 luminance elevation of the background is higher in the second interval  
786 than in the first interval (black circles). Error bars are 95% confidence  
787 intervals based on a bootstrap procedure (Knoblauch & Maloney,  
788 2012).

789  
790 Fig. 6: Results for judgment based on hue (a) and on brightness (b) depending  
791 on the presentation order for the luminance contour of the test stimulus.  
792 The information in the figure is organized in the same fashion as Figure  
793 5. The white circles are used to indicate that the luminance elevation of  
794 the inner contour is higher in the first interval than in the second  
795 interval and the black circles are used to represent a higher luminance

796 elevation of the inner contour in the second interval than in the first  
797 interval. Error bars are 95% confidence intervals.

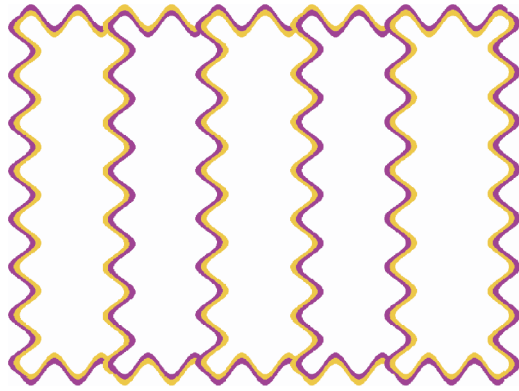
798

799 Fig. 7: Results of the estimated contributions for each combination of the two  
800 dimensions under the saturated model for four observers. The different  
801 lines are used to code the index of the background dimension (for  
802 indices 1 to 5). The top row represents the estimated contribution when  
803 judgment is based on hue and the bottom row is the estimated  
804 contribution when judgment is based on brightness.

805

806 Fig. 8 Three-dimensional surfaces for the average of the data over observers  
807 from Figure 7, showing the contributions of the inner contour and  
808 background to a) the hue and b) the brightness judgments under the  
809 saturated model.

(a)



(b)

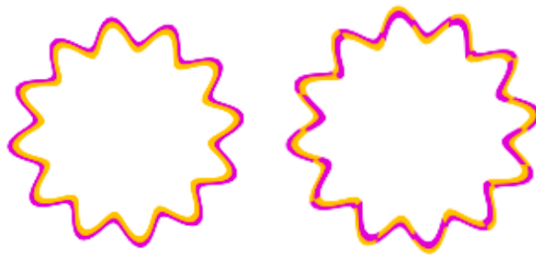


Figure 1



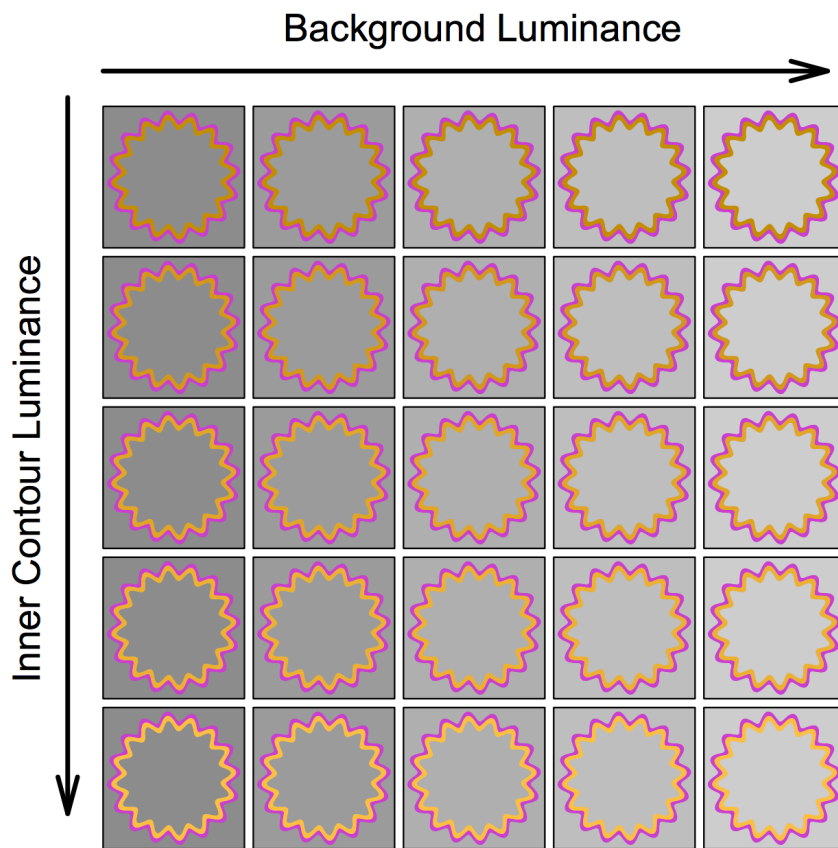
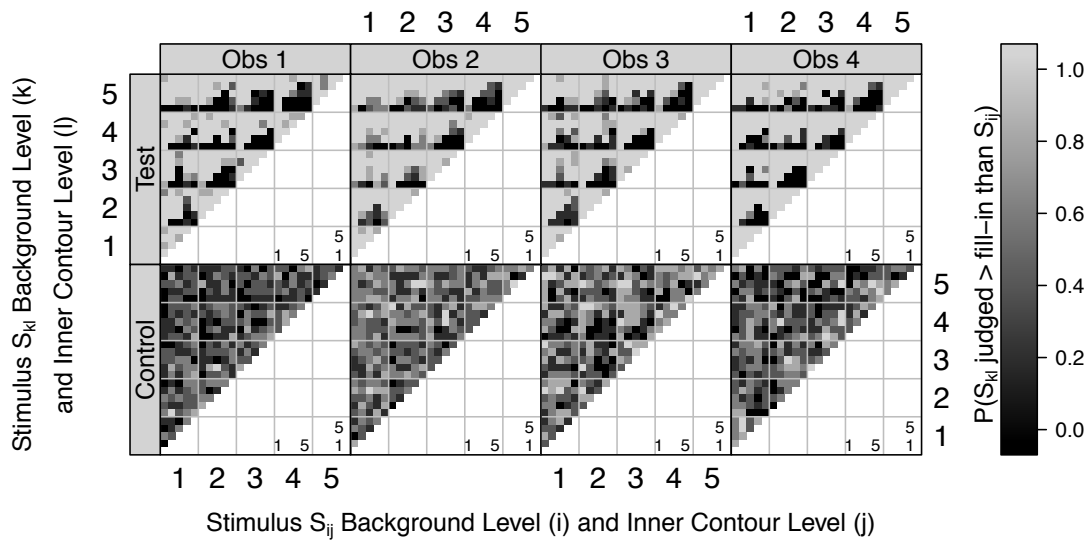
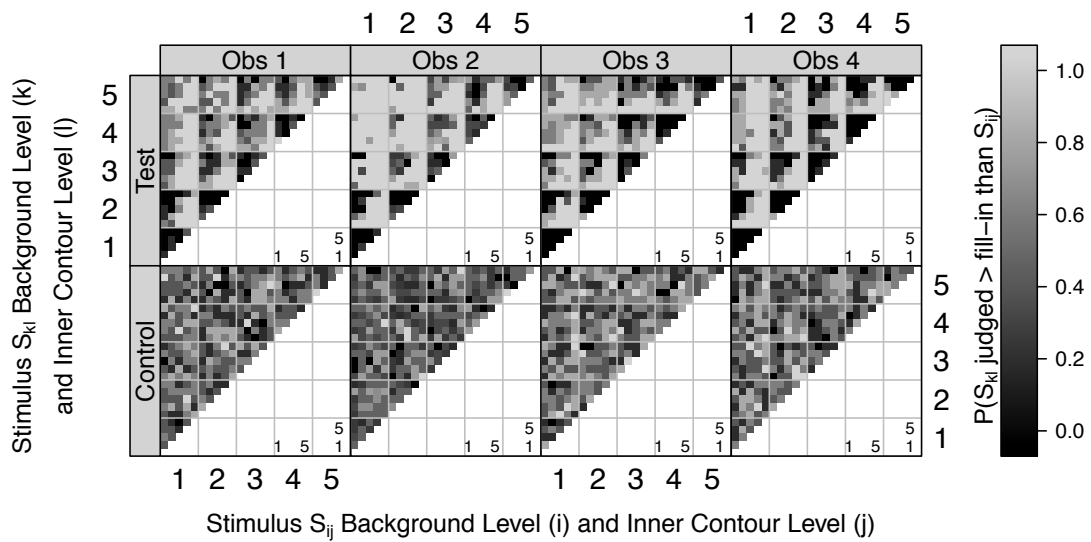


Figure 2

(a)



(b)



(c)

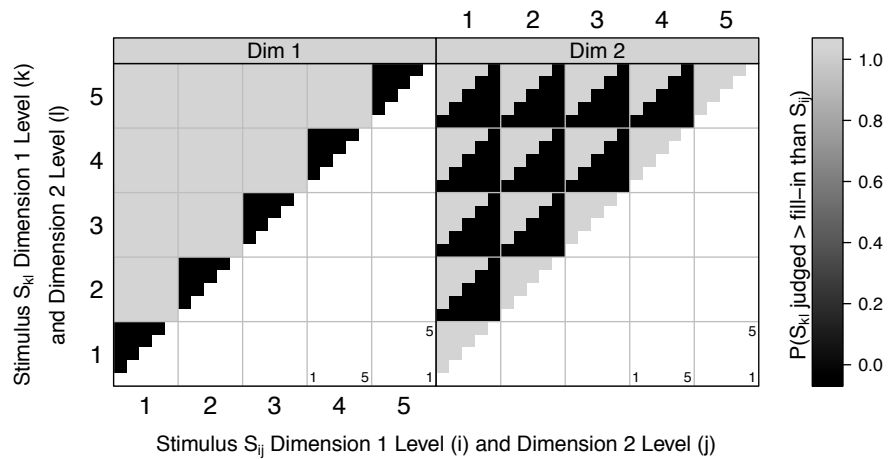
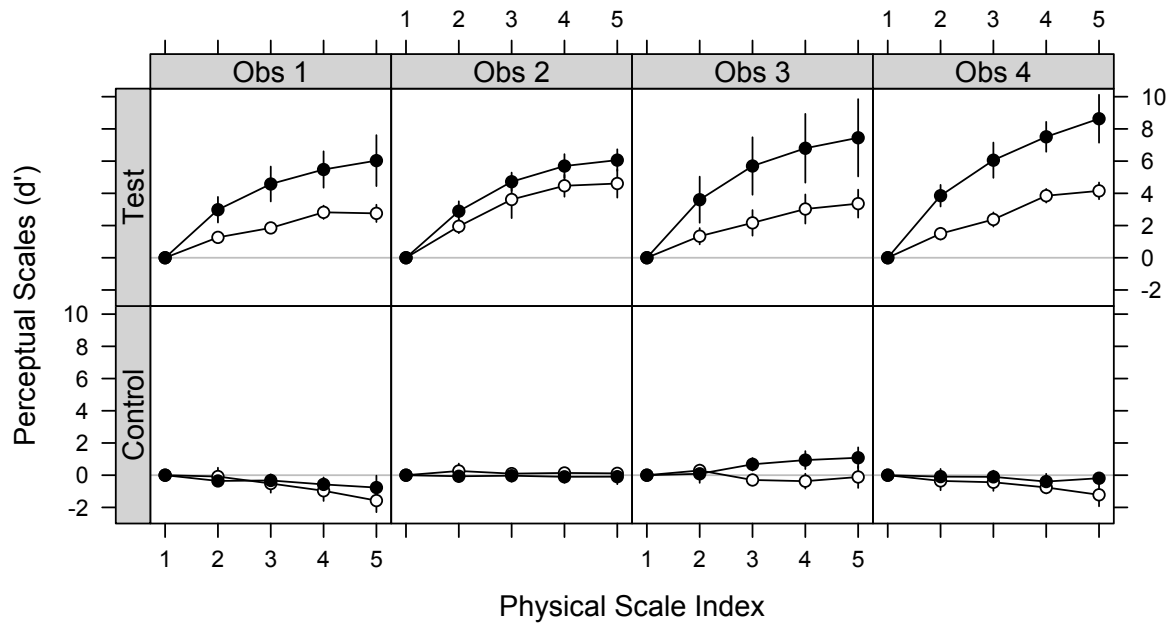


Figure 3

(a)



(b)

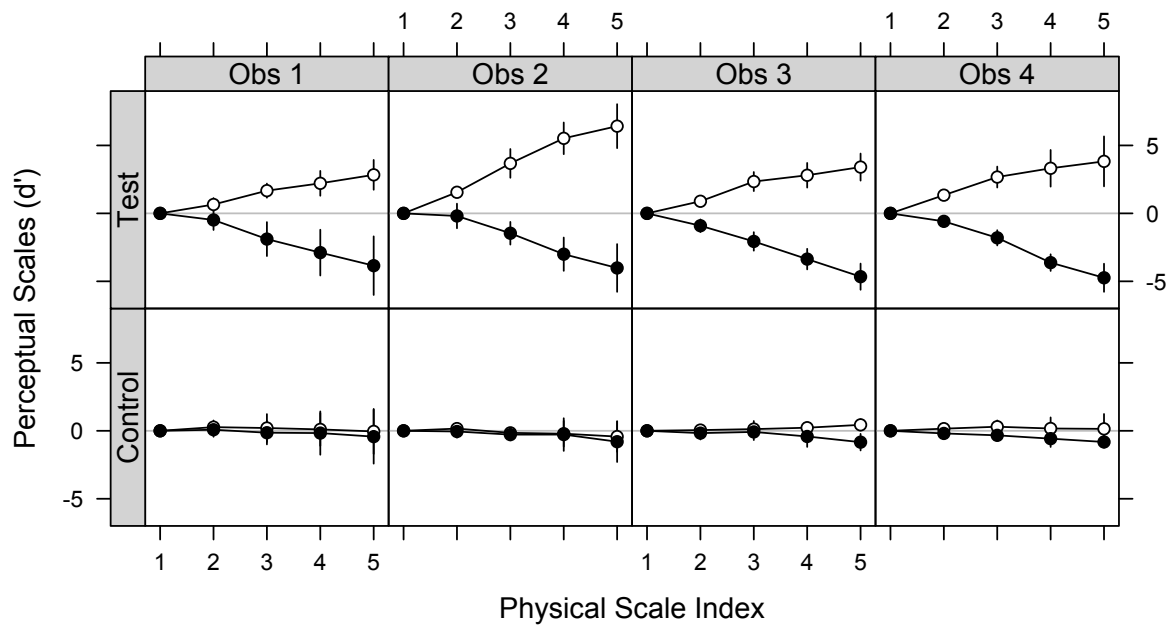
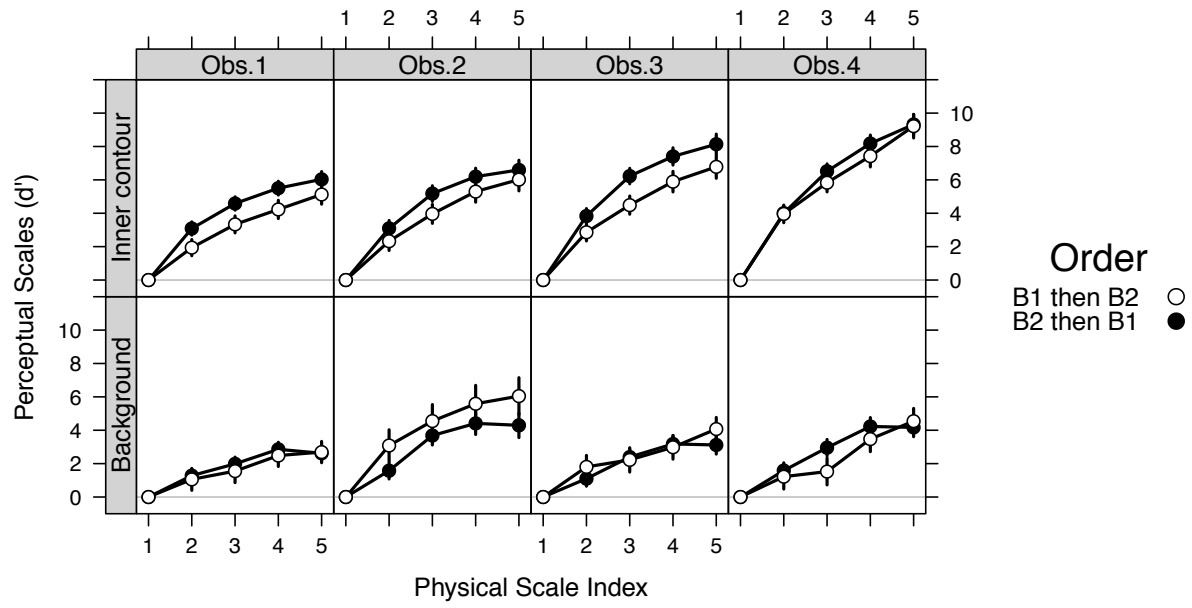


Figure 4

(a)



(b)

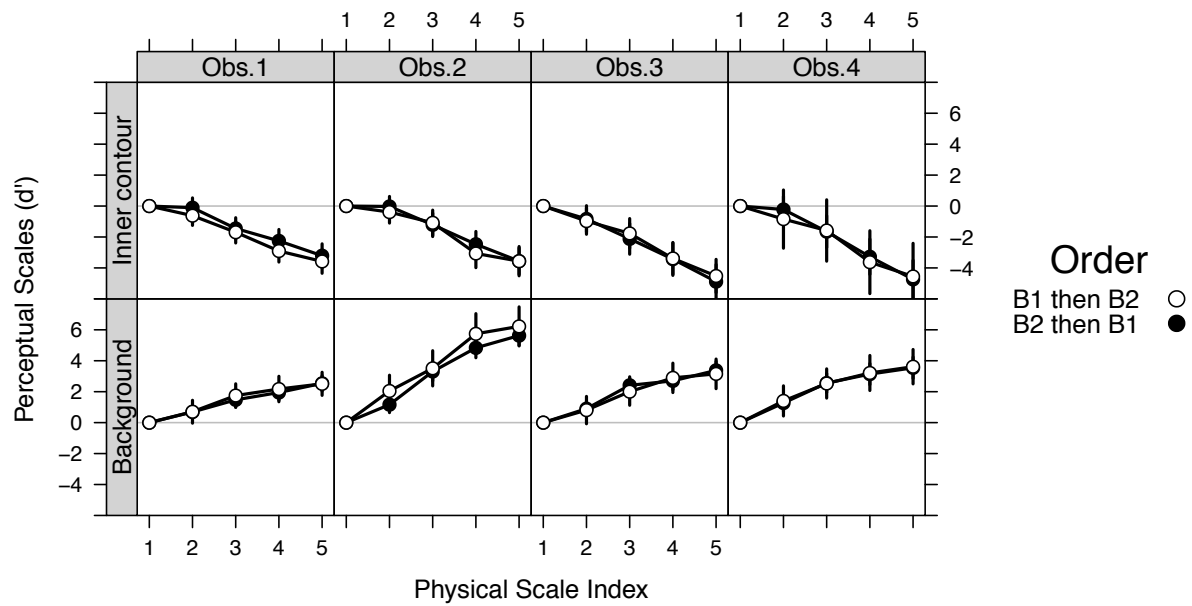
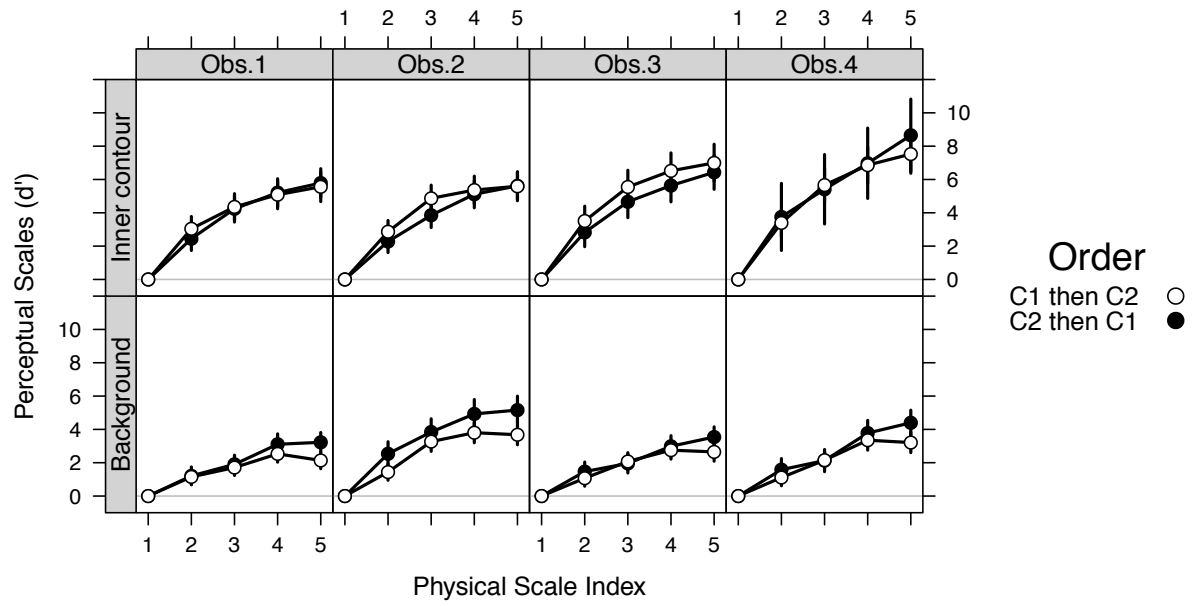


Figure 5

(a)



(b)

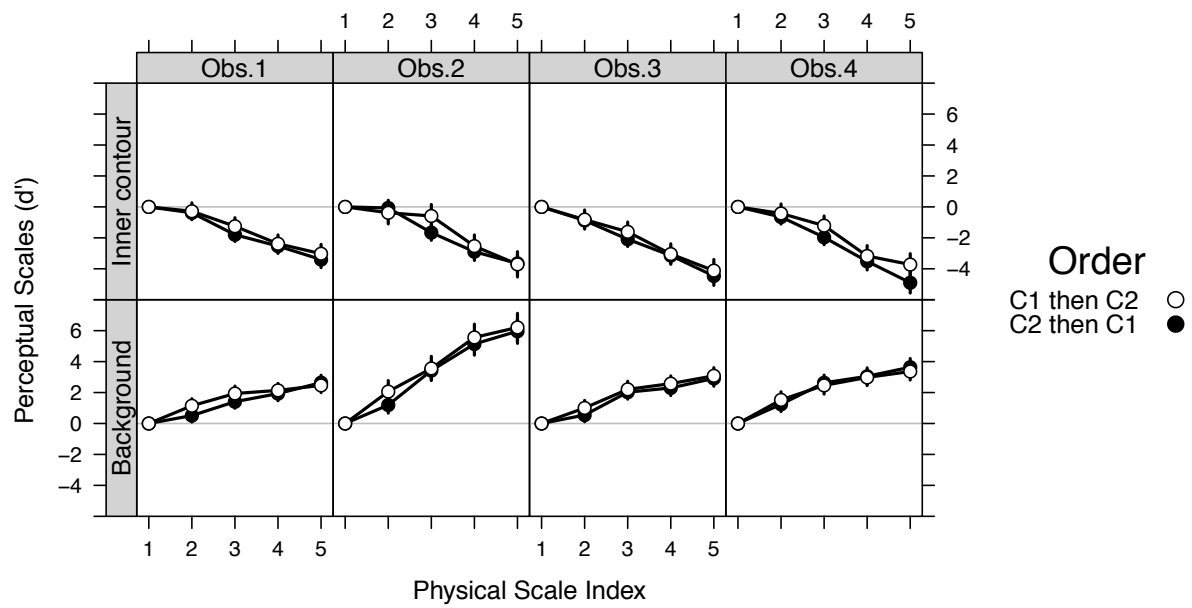


Figure 6

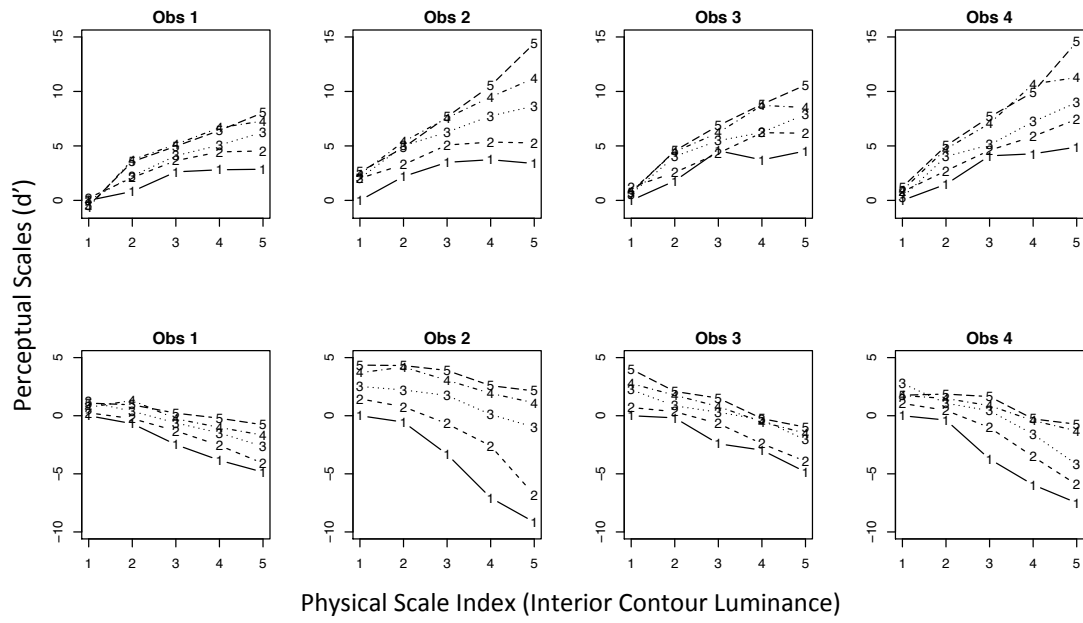


Figure 7

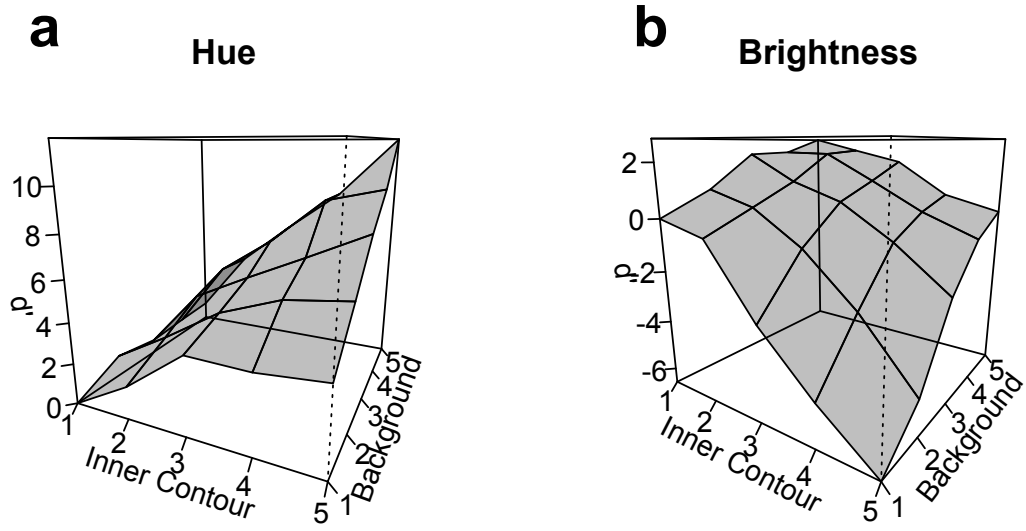


Figure 8

*Table I:* Comparison of independence and additive models for judgements based on hue

	Test stimuli (additive model × independent model)		
	Df	Deviance	p-value
Obs. 1	4	270.22	< 0.001
Obs. 2	4	568.41	< 0.001
Obs. 3	4	309.60	< 0.001
Obs. 4	4	406.38	< 0.001

*Table II:* Comparison of independence and additive models for judgement based on brightness

	Test stimuli (additive model × independent model)		
	Df	Deviance	p-value
Obs. 1	4	275.434	< 0.001
Obs. 2	4	912.11	< 0.001
Obs. 3	4	400.82	< 0.001
Obs. 4	4	430.64	< 0.001



*Table III:* Comparison of additive and saturated models for judgement based on hue

	Test stimuli (additive model × saturated model)		
	Df	Deviance	p-value
Obs. 1	16	105.44	< 0.001
Obs. 2	16	142.82	< 0.001
Obs. 3	16	104.81	< 0.001
Obs. 4	16	108.14	< 0.001

*Table IV:* Comparison of additive and saturated models for judgement based on brightness

	Test stimuli (additive model × saturated model)		
	Df	Deviance	p-value
Obs. 1	16	56.154	< 0.001
Obs. 2	16	74.01	< 0.001
Obs. 3	16	32.83	< 0.01
Obs. 4	16	122.78	< 0.001