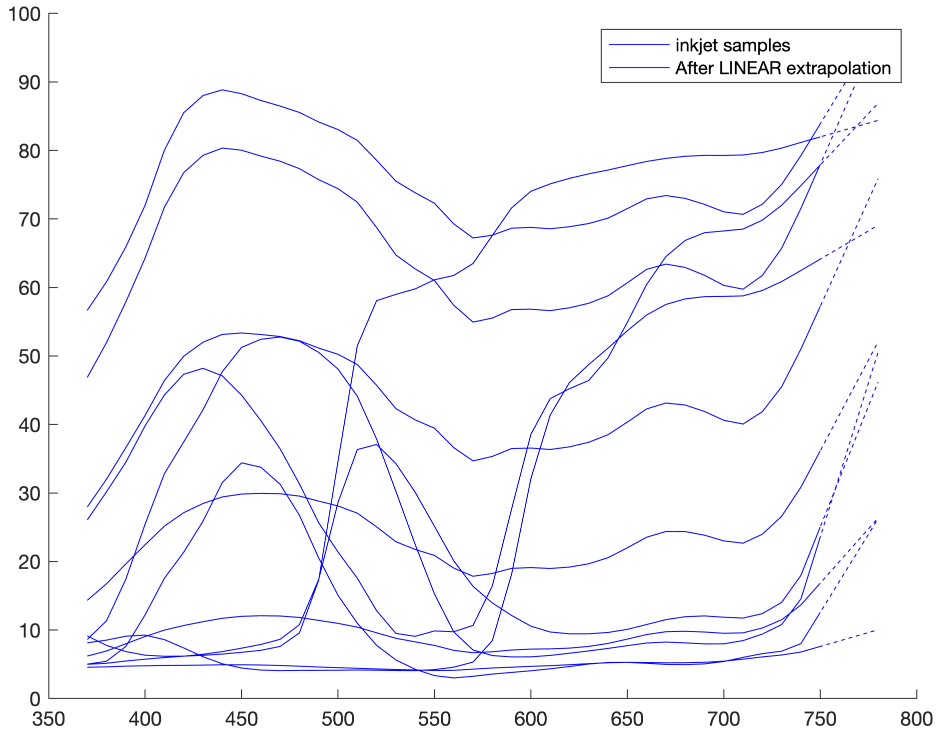
Color Differences

Github Link: https://github.com/pratheepkumar1/Principles-of-Color-Science

```
% Reading the Dataset
warning('off','all');
inkjetColorChecker_dataset = readtable("InkjetColorChecker.xlsx");
source_dataset = readtable("Illuminant Data.xlsx");
xyz_std_obs_two_deg_dataset = readtable("StdObsFuncs.xlsx",Sheet="2-degree");
patch_dataset = readtable("MacbethColorChecker.xlsx");


d_lambda = 5;
wavelength_info = 380:5:780;


%Interpolating and extrapolating the dataset (as needed)
xyz_std_obs_two_deg = interp1(xyz_std_obs_two_deg_dataset{:,1},...
    xyz_std_obs_two_deg_dataset{:,2:end},wavelength_info,"linear","extrap");
source_A = interp1(source_dataset{:,1},source_dataset.A,...
    wavelength_info,"linear","extrap");
source_D65 = interp1(source_dataset{:,1},source_dataset.D65,...
    wavelength_info,"linear","extrap");
patch_macbeth_ref = interp1(patch_dataset{2:end,1},patch_dataset{2:end,2:end},...
    wavelength_info,"linear","extrap");
inkjetColorChecker = interp1(inkjetColorChecker_dataset{2:end,1},....
    inkjetColorChecker_dataset{2:end,2:end},wavelength_info,"linear","extrap");

inkjetColorChecker_alt = interp1(inkjetColorChecker_dataset{2:end,1},...
    inkjetColorChecker_dataset{2:end,2:end},wavelength_info,"linear","extrap");



figure(1)
hold on
plot(inkjetColorChecker_dataset{2:end,1},inkjetColorChecker_dataset{2:end,2:end},...
    'Color','blue');
plot(wavelength_info,inkjetColorChecker(:,1:end),'--','Color','blue');
% plot(wavelength_info,inkjetColorChecker_alt(:,1),'--','Color','red');
legend('inkjet samples','After LINEAR extrapolation');
hold off
```



The provided dataset for inkjet color patches is available from 360nm to 750nm with 10nm difference. Whereas, Macbeth color check dataset is available from 380nm to 780nm with 5nm difference. So, the inkjet color patches (batch) data set is interpolated and extrapolated to match Macbeth patches (standard) wavelength range. For extrapolation of the dataset, there are multiple options to extrapolate such as linear, nearest, cubic. Out of this, linear extrapolation provided better dataset for the missing wavelength in have has a curve below. Above figure graphically shows the difference between before and after extrapolation of inkjet color patches.

```
% White point value of Source A and Source D65 for 2 degree observer
wp_A_two_deg_source = calcTristimulusSource(xyz_std_obs_two_deg,source_A,d_lambda);
wp_D65_two_deg_source = calcTristimulusSource(xyz_std_obs_two_deg,source_D65,d_lambda)
```

Question 1

Compute and make tables of CIELAB values of the inkjet-printed patches from the spectral reflectance data for Illuminants A and D65.

Note: Calculation for CIELAB values as written as separate function script file (calXYZtoCIELAB.m)

```
% Tristimulus value for all patches in InkjetColorChecker in A and D65 Source ...
% for 2 degree observer
tristimulus_XYZ_A_two_deg_inkjet = calcTristimulus(xyz_std_obs_two_deg,...
    source_A,inkjetColorChecker,d_lambda);
tristimulus_XYZ_D65_two_deg_inkjet = calcTristimulus(xyz_std_obs_two_deg,...
    source_D65,inkjetColorChecker,d_lambda);
```

```
%Calculate L_star, a_star, b_star, C_star for all patches in InkjetColorChecker...
% in A and D65 Source
[L_A_inkjet, a_A_inkjet, b_A_inkjet, C_A_inkjet] = calcXYZtoCIELAB...
    (tristimulus_XYZ_A_two_deg_inkjet,wp_A_two_deg_source);
[L_D65_inkjet, a_D65_inkjet, b_D65_inkjet, C_D65_inkjet] = calcXYZtoCIELAB...
    (tristimulus_XYZ_D65_two_deg_inkjet,wp_D65_two_deg_source);

CIELAB_A_inkjet = [L_A_inkjet; a_A_inkjet; b_A_inkjet; C_A_inkjet];
CIELAB_D65_inkjet = [L_D65_inkjet; a_D65_inkjet; b_D65_inkjet; C_D65_inkjet];
```

```
table_CIELAB_A_inkjet = createTableCIELAB(CIELAB_A_inkjet)
```

table_CIELAB_A_inkjet = 12×4 table

	L	a	b	C
1	184.5959	19.5152	-260.2754	261.0060
2	293.2070	-164.3398	88.3168	186.5675
3	284.0344	246.0012	182.6544	306.3972
4	449.8262	40.2241	345.0644	347.4010
5	316.2379	199.8348	-99.4567	223.2164
6	269.1174	-153.7749	-238.0972	283.4378
7	465.2040	-10.8410	-54.0476	55.1241
8	438.2126	-14.0233	-70.8735	72.2476
9	377.0793	-12.6698	-68.6518	69.8112
10	302.2152	-11.6803	-66.0798	67.1042
11	214.4527	-6.0814	-55.1579	55.4921
12	175.4062	14.3055	-7.4150	16.1130

```
table_CIELAB_D65_inkjet = createTableCIELAB(CIELAB_D65_inkjet)
```

table_CIELAB_D65_inkjet = 12×4 table

	L	a	b	C
1	199.4163	113.5982	-241.8945	267.2406
2	306.2545	-210.2871	132.5320	248.5667
3	252.9054	239.4735	125.4205	270.3292
4	438.5797	-19.7336	357.4577	358.0019
5	300.0508	235.7152	-140.3278	274.3238
6	296.6033	-81.3464	-189.9710	206.6548
7	468.7054	-1.1817	-49.4727	49.4868
8	442.8954	-1.6201	-64.5035	64.5238

	L	a	b	C
9	381.7105	-2.5360	-61.6913	61.7434
10	306.7505	-2.9144	-58.8462	58.9184
11	217.9386	1.3599	-49.7422	49.7608
12	174.4609	15.2857	-9.8599	18.1898

Question 2 (Prerequisite Calculations)

Calculating CIELAB values for Macbeth refpatches

```
% Tristimulus value for all patches in InkjetColorChecker in A and D65 Source...
% for 2 degree observer
tristimulus_XYZ_A_two_deg_macbeth_ref = calcTristimulus(xyz_std_obs_two_deg,...
    source_A,patch_macbeth_ref,d_lambda);
tristimulus_XYZ_D65_two_deg_macbeth_ref = calcTristimulus(xyz_std_obs_two_deg,...
    source_D65,patch_macbeth_ref,d_lambda);

%Calculate L_star, a_star, b_star, C_star for all patches in InkjetColorChecker...
% in A and D65 Source
[L_A_macbeth_ref, a_A_macbeth_ref, b_A_macbeth_ref, C_A_macbeth_ref] = ...
    calcXYZtoCIELAB(tristimulus_XYZ_A_two_deg_macbeth_ref,wp_A_two_deg_source);
[L_D65_macbeth_ref, a_D65_macbeth_ref, b_D65_macbeth_ref, C_D65_macbeth_ref] = ...
    calcXYZtoCIELAB(tristimulus_XYZ_D65_two_deg_macbeth_ref,wp_D65_two_deg_source);

CIELAB_A_macbeth_ref = [L_A_macbeth_ref; a_A_macbeth_ref; b_A_macbeth_ref;...
    C_A_macbeth_ref];
CIELAB_D65_macbeth_ref = [L_D65_macbeth_ref; a_D65_macbeth_ref; b_D65_macbeth_ref;...
    C_D65_macbeth_ref];

table_CIELAB_A_macbeth_ref = createTableCIELAB(CIELAB_A_macbeth_ref);
table_CIELAB_D65_macbeth_ref = createTableCIELAB(CIELAB_D65_macbeth_ref);
```

Question 2

Calculate and make tables of ΔL*, Δa*, Δb*, ΔC*, ΔH*, ΔE*ab and ΔE*00 color differences *(Please put columns in this order to make grading easier!)* between the 12 corresponding patches on the inkjet-printed ColorChecker (sample set) and the real ColorChecker (reference set). You can calculate ΔE*00 with the provided m-file (it takes Lab arrays in 3xN orientation), but please write you own Matlab code for the other differences. Please make a two tables: one for the D65 data and one for the A data.

Note: Calculation for color difference values as written as separate function below

```
% Delta calculation for A
deltaL_A = deltaL(L_A_inkjet,L_A_macbeth_ref(:,13:24));

deltaa_A = deltaa(a_A_inkjet,a_A_macbeth_ref(:,13:24));
```

```
deltab_A = deltab(b_A_inkjet,b_A_macbeth_ref(:,13:24));

deltaC_A = deltaC(C_A_inkjet,C_A_macbeth_ref(:,13:24));

deltah_A = deltah(CIELAB_A_inkjet,CIELAB_A_macbeth_ref(:,13:24));

deltaH_A = deltaH(C_A_inkjet,C_A_macbeth_ref(:,13:24),deltah_A);

deltaEab_A = deltaEab(deltaL_A,deltaC_A,deltaH_A);

deltaE00_A = deltaE00(CIELAB_A_inkjet,CIELAB_A_macbeth_ref(:,13:24));

color_diff_A = [deltaL_A; deltaa_A; deltab_A; deltaC_A; deltaH_A; deltaEab_A; deltaE00_


% Delta calculation for D65

deltaL_D65 = deltaL(L_D65_inkjet,L_D65_macbeth_ref(:,13:24));

deltaa_D65 = deltaa(a_D65_inkjet,a_D65_macbeth_ref(:,13:24));

deltab_D65 = deltab(b_D65_inkjet,b_D65_macbeth_ref(:,13:24));

deltaC_D65 = deltaC(C_D65_inkjet,C_D65_macbeth_ref(:,13:24));

deltah_D65 = deltah(CIELAB_D65_inkjet,CIELAB_D65_macbeth_ref(:,13:24));

deltaH_D65 = deltaH(C_D65_inkjet,C_D65_macbeth_ref(:,13:24),deltah_D65);

deltaEab_D65 = deltaEab(deltaL_D65,deltaC_D65,deltaH_D65);

deltaE00_D65 = deltaE00(CIELAB_D65_inkjet,CIELAB_D65_macbeth_ref(:,13:24));

color_diff_D65 = [deltaL_D65; deltaa_D65; deltab_D65; deltaC_D65;...
    deltaH_D65; deltaEab_D65; deltaE00_D65];
```

```
table_color_diff_A = createTableColorDiff(color_diff_A)
```

table_color_diff_A = 12×7 table

	ΔL	Δa	Δb	ΔC	ΔH	ΔEab	ΔE00
1	157.4962	16.9687	-206.2099	206.8806	3.3010	260.0299	89.2330
2	239.7107	-128.1525	61.1273	141.3039	13.8855	278.6051	87.2487
3	236.1828	189.2705	144.9657	238.2883	7.5525	335.5900	89.9260
4	365.4149	30.4179	267.7938	269.5106	1.6756	454.0560	89.5657
5	260.6825	151.7377	-94.7171	174.8864	-37.5553	316.1503	89.7898

	ΔL	Δa	Δb	ΔC	ΔH	ΔEab	ΔE00
6	222.2238	-121.2739	-202.4523	235.2001	19.3698	324.1569	89.3126
7	369.7276	-10.8827	-54.5595	54.6105	10.6240	373.8899	86.7917
8	357.2371	-14.0767	-70.9962	72.1138	6.1822	364.4955	90.5516
9	310.6992	-12.5058	-68.5847	69.6339	3.3727	318.4246	91.0154
10	250.0350	-11.5504	-66.0081	66.9559	2.7196	258.8590	90.0339
11	178.0238	-5.5958	-54.6480	54.7879	3.9994	186.3067	86.9314
12	154.0582	14.6212	-6.4387	15.0868	5.2558	154.8843	90.7439

```
table_color_diff_D65 = createTableColorDiff(color_diff_D65)
```

table_color_diff_D65 = 12×7 table

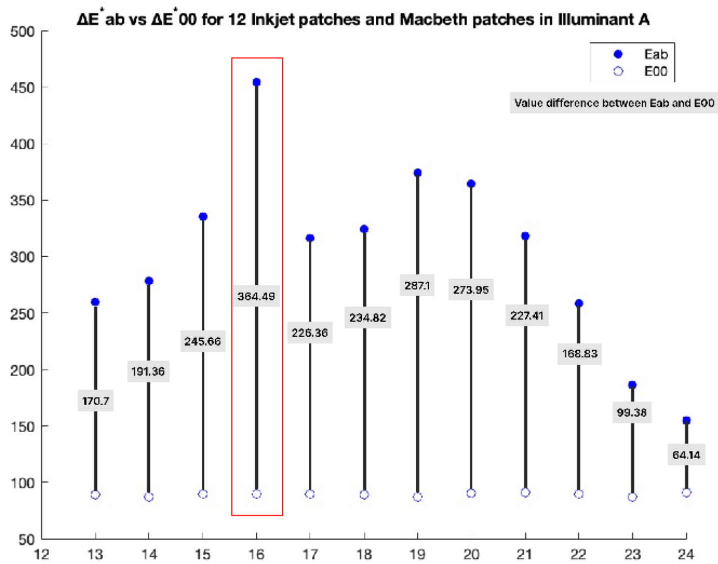
	ΔL	Δa	Δb	ΔC	ΔH	ΔEab	ΔE00
1	169.4302	88.9892	-191.0292	210.7349	-1.4207	270.4030	89.8717
2	250.5993	-168.6047	97.7573	194.2831	15.4303	317.4650	88.2284
3	211.9680	186.6256	99.8130	211.6040	3.9363	299.5366	90.0391
4	356.9388	-18.1581	277.9834	278.5121	5.9594	452.7801	89.7647
5	249.0507	186.2906	-125.2887	222.6618	-28.6912	335.3024	90.7028
6	244.9170	-56.6194	-163.9887	170.7869	30.4938	300.1372	89.7179
7	373.2407	-0.8246	-50.2508	48.6308	12.6833	376.6091	86.8688
8	361.9429	-1.7618	-64.6365	64.3294	6.5356	367.6733	90.5891
9	315.3305	-2.5827	-61.6199	61.6581	-1.3994	321.3052	91.3300
10	254.5697	-2.9723	-58.7607	58.8150	-1.5643	261.2803	90.4474
11	181.4605	1.5503	-49.2676	49.2494	2.0481	188.0362	87.0914
12	153.0483	15.3197	-8.9129	17.2422	4.1037	154.0711	90.5699

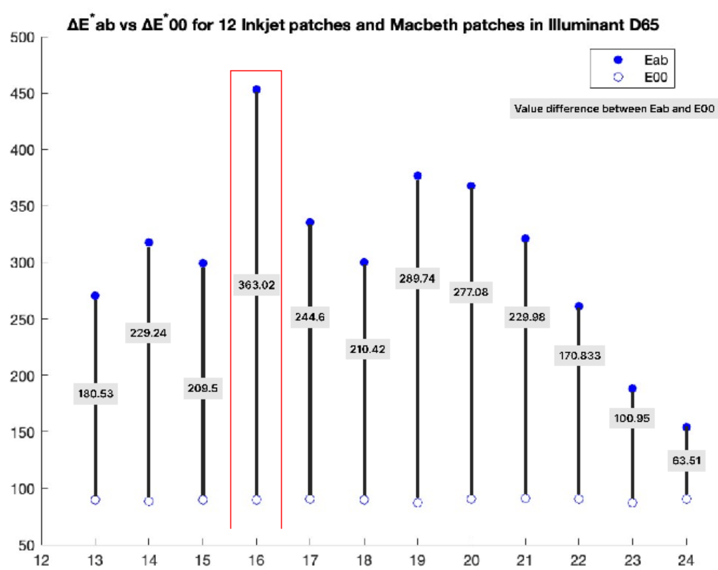
Question 3

Discuss your results, including what you observe between the two ΔE metrics and what you lose by using a ΔE value as opposed to its components (ΔL*, Δa*, Δb*, ΔC*, ΔH*).

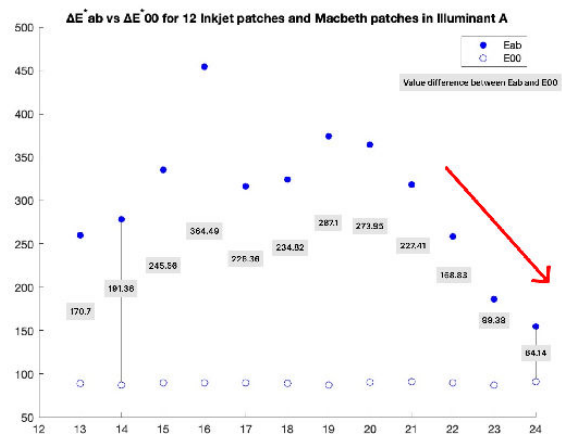
- E00 results are normalized and optimized better than E65 for estimating the color difference which will be good for comparison with visual color difference. Also, E00 has significantly lower standard deviation (S.D = 1.4) in color difference for the given batch when compared to Eab (S.D: 78.25). This difference for E00 is acheived by normalizing Eab with the weightness color difference parameter with recirpocal weight and position function.
- For chromatic patches, the color with higher chromatic difference difference (Path 16), value has greater difference in value between two ΔE metrics for both the illuminant A and D65. Chromatic difference have

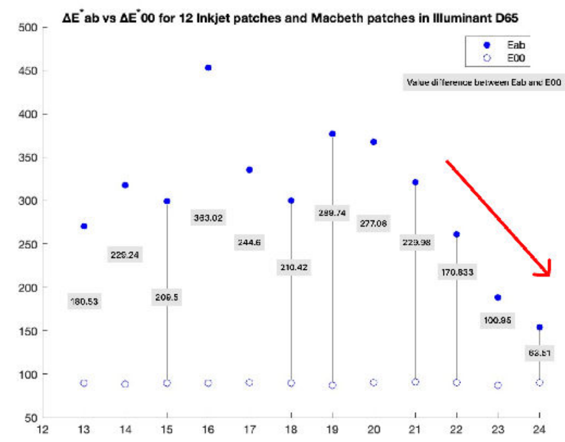
a bigger magnitude in color euclidean difference calculation. That's why chromatic changes are very noticeable while comparing chromatic color pairs.





- Whereas for achromatic patches, colors with higher lightness difference (Path 19) impact the difference in value between two ΔE metrics for both the illuminant A and D65. I doubt that this gradual decreases in difference between two ΔE metrics for decreasing lightness for achromatic patches might correlate with the compressive response.



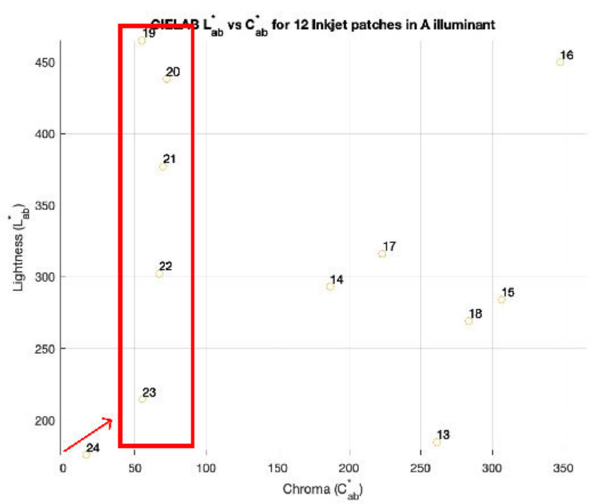


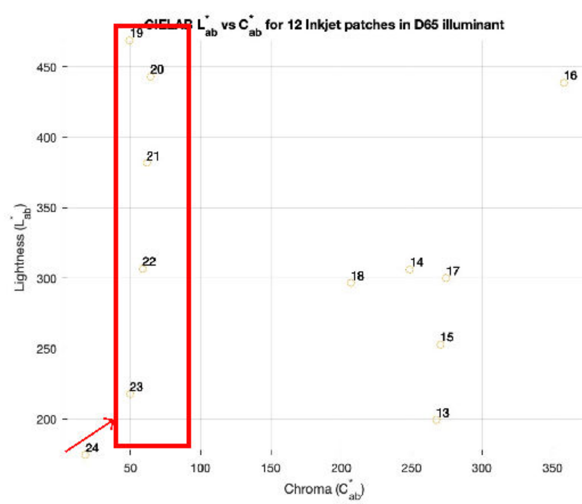
- We will loose the quantification of visual color specifications as such lightness, chroma, hue while using ΔE value. Also, while plotting the Δa* vs Δb*, ΔC* vs ΔL*, ΔH* we can have a colored background to specify the standard and batch colors position with respect to it's coordinates for that specification. But plotting ΔE don't give such information, rather we can use it to compare how much difference it has between visual difference. So to summarize, it is a mathematical representation of sensation difference where as other components are mathematical representation color specification differences

Question 4

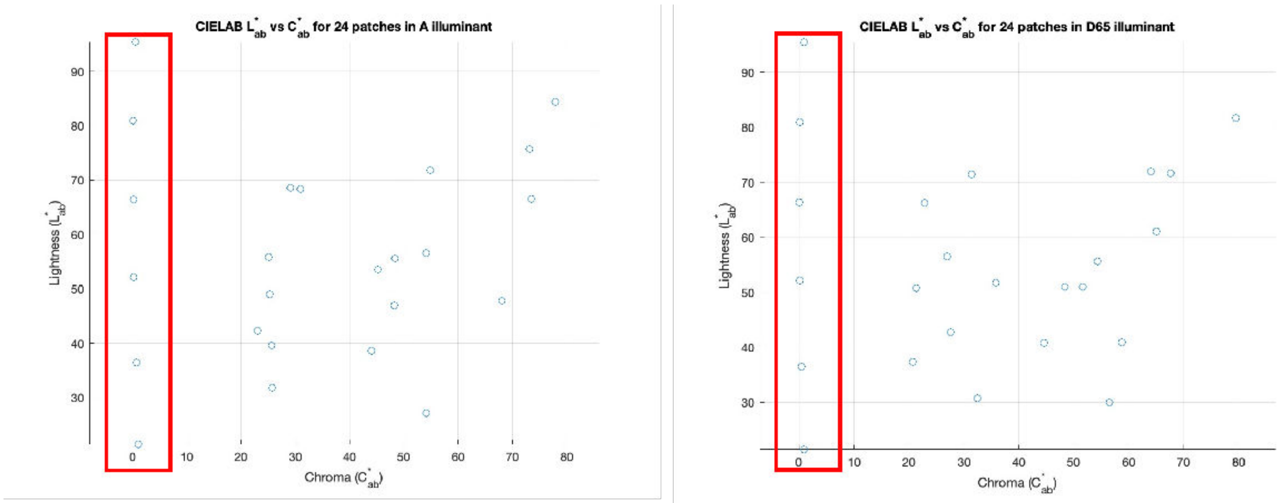
Under which illuminant is the inkjet print a better match to the real ColorChecker?

- In general, inkjet add more chroma to achromatic color patches (shown in below figures). This chromatic addition tends to move towards bluish color for achromatic patches. If we try to analyse the difference based on Euclidean distance, the one illuminant have outperformed the other in the certains patches. That is, some patches has less euclidean distance in illuminant A whereas some patch in illuminant A has more Eucledian difference than illuminant D65.





Inkjet Patch



Macbeth Patch

- Instead of choosing a better illuminant overall for all patches, I decided to choose a better illuminant each each color and it's properties. For green and blue patches (Patch 12 and 13) , inkjet patches under illuminant A matches better with the standard batch. But if the chroma of those colors increases (especially patch 18 - blue), illuminant D65 is better.
- Whereas, for achromatic batches, illuminant A is better because it counterbalances the additional blue color effect produced by the inkjet. This counterbalancing happens because of the yellowish nature of illuminant A (Incandescent Light)

Functions

```
%Function to create table and assign CIELAB values
```

```
function a2t = createTableCIELAB(values)
    a2t = array2table(values');
    a2t.Properties.VariableNames(1:4) = {'L','a','b','C'};
end

function a2t = createTableColorDiff(values)
    a2t = array2table(values');
    a2t.Properties.VariableNames(1:7) = {'ΔL','Δa','Δb','ΔC','ΔH','ΔEab','ΔE00'};
end

%Function to calculate Delta L
function DL = deltaL(L_bat,L_std)
    DL = L_bat - L_std;
end


%Function to calculate Delta a
```

```
function Da = deltaa(a_bat,a_std)
    Da = a_bat - a_std;
end


%Function to calculate Delta b
function Db = deltab(b_bat,b_std)
    Db = b_bat - b_std;
end

%Function to calculate Delta C*
function DC = deltaC(C_bat,C_std)
    DC = C_bat - C_std;
end


%Function to calculate Delta h
function Dh = deltah(bat,std)
    Dh = hueAngle(bat(2,:),bat(3,:)) - hueAngle(std(2,:),std(3,:));
end


%Function to calculate hue angle
function h = hueAngle(a,b)
    h = atan2Deg(b,a);
end


%Function to calculate Delta H
function DH = deltaH(C_bat,C_std,deltah)
    DH = 2*(C_bat.*C_std).^(1/2).*sinDeg(deltah./2);
end


%Function to calculate Delta Eab
function e = deltaEab(deltaL,deltaa,deltab)
    e = sqrt(deltaL.^2 + deltaa.^2 + deltab.^2);
end


function out = atan2Deg(inY,inX)
    out = atan2(inY,inX).*180./pi;
    out = out+(out<0).*360;
end


function out = sinDeg(in)
    out = sin(in.*pi./180);
end
```