Analyzing afterimage strength and duration test results with k-means clustering

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Abstract

Afterimages are common and frequent perceptual phenomena of everyday life. A typical appearance is the negative "ghost" image of a bright light source when we turn away from it. In the case of significant colour contrast, the afterimage can be coloured. The strength of the perceived false image decreases gradually and completely disappears in a 10–100-s timescale. The underlying processes have multiple components: a quick adaptation on the retinal level, and a slower adaptation on the cortical level. The phenomenon of afterimage has a potential application in ergonomic and visual design fields. In our former research, we examined the effect of gender and age on afterimage strength and duration. We asked test subjects to observe and evaluate the duration and "strength score" of the same light-transitions. Two sets of experiments were performed: colour-colour transitions with 41 and colour-grey transitions with 16 test subjects between 19 and 62. We found that gender has no measurable influence, but age makes a difference to a great extent. Both experiments confirmed that over 40 years the average duration of colour afterimages decreases. In our current study we examined the dependence of afterimage parameters on colourimetry parameters. We found that duration and strength depend on chroma change, but the direction of the colour transition in the a*-b* (green-red and blue-yellow) plane is also essential. The importance of magenta-green colour transition was revealed by k-means cluster analysis, but the number of tests should be increased for a final conclusion.

Keywords: afterimage duration, afterimage strength, visual design, ergonomy, clustering

Introduction

In human vision, afterimage is an illusionary image appearing after having been exposed to the primary one (Smith et al., 1983; Rinner, Gegenfurtner, 2000; Zaidi et al., 2012; Kingdom et al., 2020). For instance, during driving at night, if we stare into the headlights of cars approaching us in the opposite lane and finally turn our eyes away, the negative afterimage of bright light sources remains perceived (Mikamo et al., 2013). This afterimage fades gradually and totally disappears in a 10-100-s timescale but the duration time and the subjective strength of the afterimage perceived show high personal variance.

Our previous test series

In our previous works (Garai, Horváth, 2021, Garai, Horváth, 2022), we tried to examine the longest duration and most "intense" afterimages in the first ("Colour-Colour") series of measurements. Therefore, we used colours from the edge of the monitor's gamut of the highest luminosity for background and foreground colours. In the second, confirmatory test series ("Colour-Grey"), we used grey backgrounds in all cases and used test colours with the same luminance.

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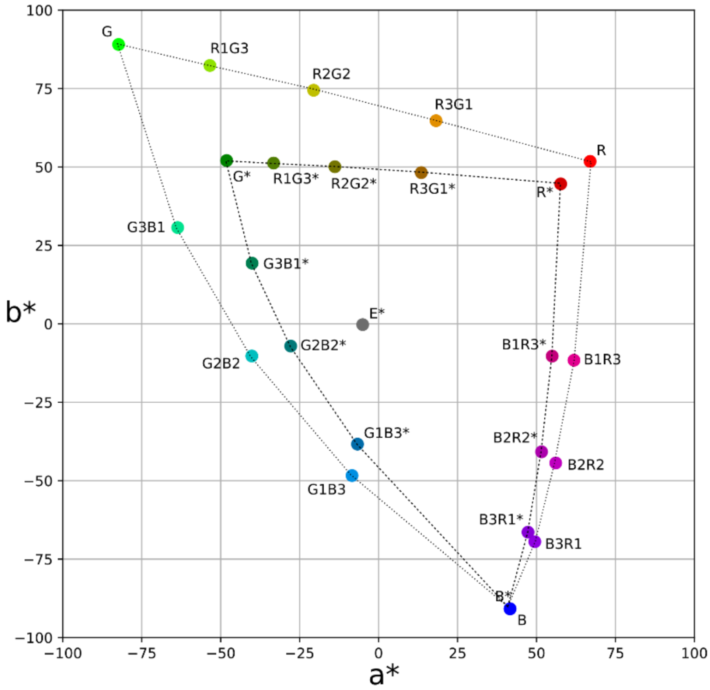
To mathematically express the colours involved in our experiment, we used an internationally accepted colour coordinate system, the CIE L*a*b* colour space (Schanda, 2007; Markovic et al., 2013), where CIE abbreviates the organization Comission International de l'Eclairage. Colours in this colour space are expressed in three-dimension by the coordinates L* as luminance, a* as the yellow-green colour component and b* as the red-green colour component. For later reference in our paper, the colours involved in our test series are shown in a simplified way, in two dimensions by CIE a*b* chromaticity diagram on Figure 1.

Figure 1: *Test colours of Colour-Colour (denoted without *) and Colour-Grey experiments (with *) on the CIE a*b* plane.*



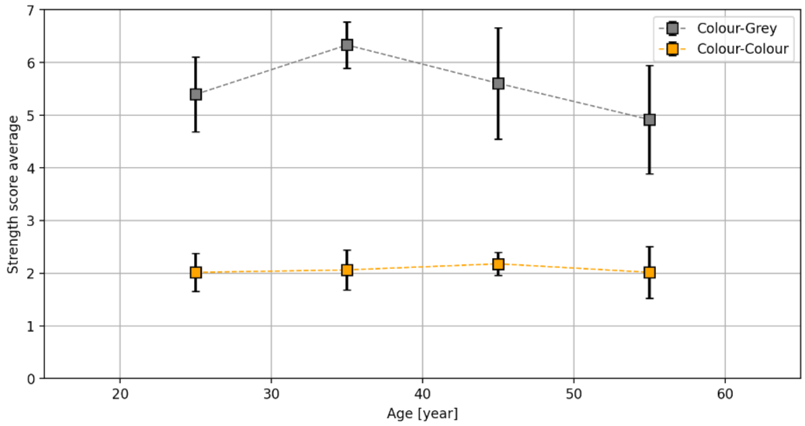
Source: *Own work*

Summary of our previous results

Significant differences in duration time were observed between test subjects in the preliminary experiment. Some of them measured duration time between 10 and 20 s while others could observe the afterimages typically over 40 seconds. We found that the afterimage strength ($s_{aftimavg}$) and duration ($t_{aftimavg}$) was not significantly influenced by gender by statistical analysis, t-test and Mann-Whitney test. The effect of age on afterimage strength and duration was evaluated by a detailed comparison, 10-year age intervals grouped the whole result set. (61 and 62-year-old persons were categorised into the 50-60 group, the only 19-year-old test subject was included in the 20-29 category.)

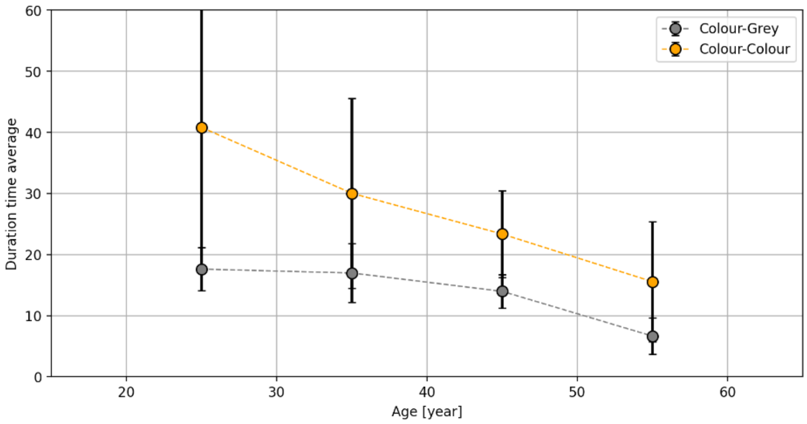
For a visual comparison of $s_{aftimavg}$ and $t_{aftimavg}$, the error bar method (Nicholls, 2016) was used. The length of error bars represents the 2-sigma values where sigma is the estimated deviation of the average value. Figure 2 shows the strength score, Figure 6 the duration time values.

Figure 2: *Strength score averages in 10-year long bins for Colour-Colour and Colour-Grey experiments.*



Source: *Own work*

Figure 3: *Duration time averages in 10-year long bins for Colour-Colour and Colour-Grey experiments.*



Source: *Own work*

It is clear from Figure 2 that strength scores have no measurable age-dependence both in Colour-Colour and Colour-Grey case. It was confirmed with t-test and Mann-Whitney test calculations at alpha=0.05.

Figure 3 shows that duration time averages have relevant differences between 10-year age groups. Table 11 shows the duration time comparison results for Colour-Colour experiments. Due to the low number of test persons in the age groups, the difference between neighbouring groups is not significant at alpha=0.05, but we found several apparent differences between the second neighbours.

Further evaluation of our afterimage test results

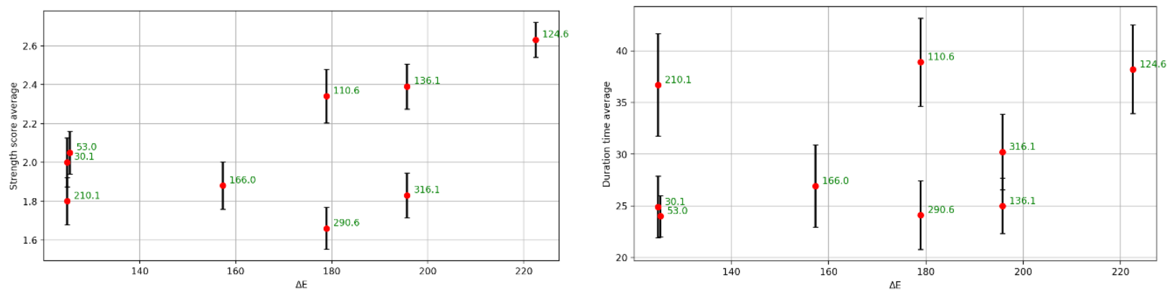
Colour dependence of the parameters

In the previous subsections, we worked with averages of overall colours. An important question is whether the duration time and strength score average values over the test persons have a colour dependence or not. The first idea should be that these parameters correlate with a colourimetry parameter that describes the difference of the foreground and background colours of the transition like difference in luminance (ΔL^*), colour contrast (ΔC), or their combination $\Delta E^*=(\Delta L^{*2}+\Delta C^2)^{1/2}$ expressed in the CIE L*a*b* colour space.

Calculations with Colour-Colour experiment data did not give a remarkable correlation between ΔL^*, ΔC, ΔE^* and duration time or score strength. Figure 4 shows the strength score and duration time averages as a function of ΔE^*. Here the error bars show the expected

deviation of the average value. Therefore, if two error sticks partly overlap each other, the difference is not significant. The small numeric labels near the markers show the direction angles (θ) of the transition.
Figure 4 shows no clear tendency in ΔE*-dependence; therefore, we cannot state that the colour difference of foreground and background colour in CIE L*a*b* system predicts the strength score and duration time.

Figure 4: *Strength score (left) and duration time (right) averages in Colour-Colour experiments as a function of ΔE*. Labels show the direction angle (θ) of the transition.*

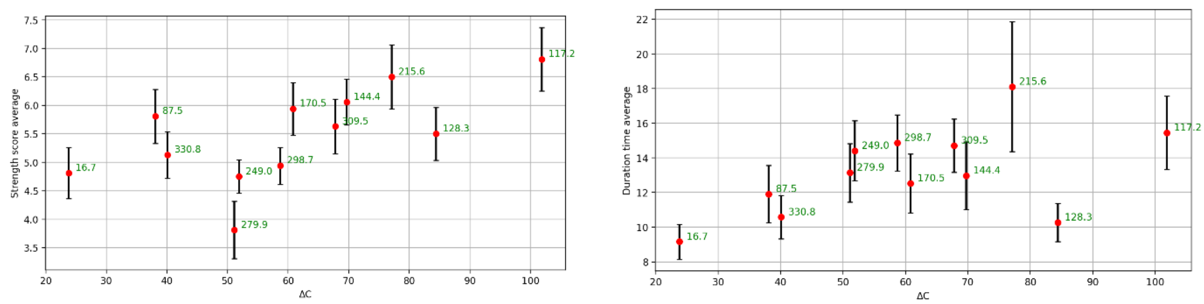


Source: *Own work*

Although another interesting phenomenon appears here: dependence on transition direction. We have 3 “reverse pairs” in the Colour-Colour experiments: R↔G2B2 (θ=30.1 and 210.1), G↔B2R2 (θ=136.1 and 316.1), B↔R2G2 (θ=110.6 and 290.6). The last one shows a significant difference in both duration and strength score: transition from B (blue) to R2G2 (yellow) produces a measurably longer duration time and stronger afterimage than the opposite direction. Similarly, R→G2B2 (θ=210.1) has a significantly longer duration time than the opposite pair while R2B2→G (θ=136.1) seems to produce higher strength scores. This asymmetry clearly shows that the duration time and strength of afterimages depend on the direction to a great extent although a larger number of measurements are needed to study this effect in detail.

The situation is similar in the Colour-Grey experiment. The results are presented in Figure 5. Probably due to the smaller relative standard deviation in measured parameters, we can observe a biased increasing tendency in both strength and duration as a function of ΔC. (Remember: in this case ΔL*=0, therefore ΔE*=ΔC.)

Figure 5: *Strength score (left) and duration time (right) averages in Colour-Grey experiments as a function of ΔC. Labels show the direction angle (θ) of the transition.*



Source: *Own work*

The measurement uncertainty is too high to construct a formula that describes duration time and strength score as a function of ΔC, but the tendency is clear.

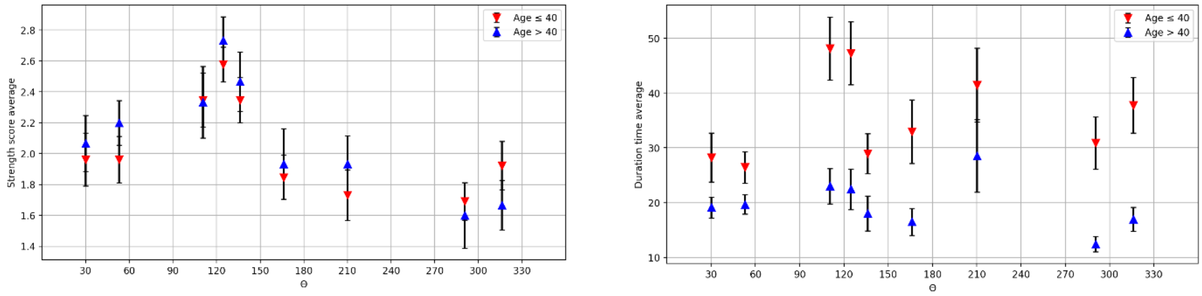
Due to the method of transition choice, in the Colour-Grey experiments, we do not have such opposite direction pairs as in the Colour-Colour experiments. Therefore, we cannot perform the same comparisons that we did in that case. The only thing that suggests some transition direction dependence is that R3G1*→E* (θ=249.0), R2G2*→E* (θ=279.9), and R1G3*→E* (θ=298.7), are below the trend line of the other cases in the ΔC-strength diagram. It means that yellowish-to-grey transitions produce less strong afterimage than expected from the ΔC value.

As a summary of this subsection, we can conclude that despite the high variance of personal data, the following statements are true. In Colour-Grey experiments with ΔL*=0 and ΔC<102, both duration time and strength score show increasing tendency with ΔC, while in Colour-Colour experiments, with ΔE>120, no such dependence measured. Moreover, the measured parameters are dependent on transition direction: blue to yellow transition shows significantly longer a stronger afterimage than the yellow-to-blue opposite pair (with precisely the same colour stimuli), while yellow to grey transition shows a smaller strength score than the other colour-to-grey transition with similar ΔC value.

Age dependence of the parameters of individual transitions

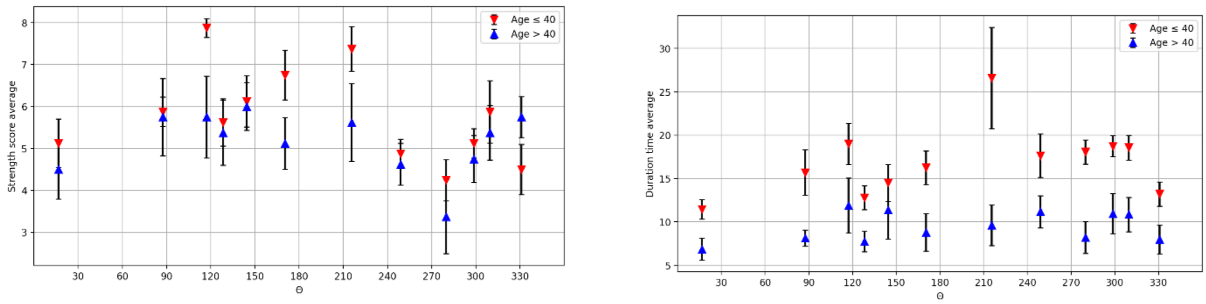
We also examined the differences in strength scores and duration time values for individual transitions between younger (age ≤ 40) and older (age>40) groups. Figures 6 and 7 show these diagrams for Colour-Colour and Colour-Grey experiments.

Figure 6: *Strength score (left) and duration time (right) averages in Colour-Colour experiments as a function of transition direction (θ) for younger and older groups.*



Source: *Own work*

Figure 7: *Strength score (left) and duration time (right) averages in Colour-Grey experiments as a function of transition direction (θ) for younger and older groups.*



Source: Own work

Based on the presented error bars, we can presume that age makes no significant change in strength scores but produces a notable difference in duration times. The calculations with t-test and Mann and Whitney test proved that for Colour-Colour experiments, we have a significant difference in the following cases: B→R2G2 (θ=110.6), B→G (θ=124.6) and

R2G2→B (θ=290.6). For Colour-Grey transitions, we have a statistically significant difference in the following cases: R2G2*→E* (θ=279.9), R1G3*→E* (θ=298.7), G*→E* (θ=309.5), G1B3*→E* (θ=87.5).

The transitions listed in the previous paragraph are the most sensitive ones to the age difference. It can be a clue to the explanation that yellow-green shades play an essential role in most of them. It is possible that the yellowing of the eye lens plays an important role. An important fact is that for all the transitions, younger test subjects produced higher duration time averages than the older ones, but in most cases, the difference is not significant at $\alpha = 0.05$ level.

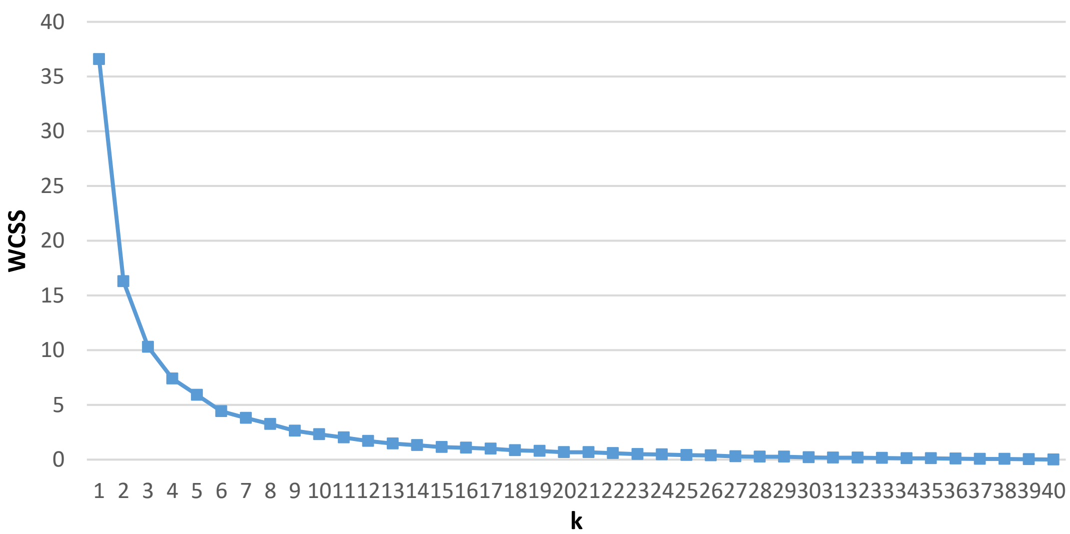
Finally, we remark that R*→E* (θ=215.6) case show a remarkable difference on the right-side diagram of Figure 8, but the statistical tests do not confirm this difference at $\alpha = 0.05$ level. This transition was a peculiar one: it produced significantly longer duration time on average among the younger test subjects, but the personal variance was extremely high.

Cluster analysis

The significant variation between different test subject results raised the question of whether test subjects may be grouped by difference in afterimage perception of particular fast colour transitions. For example, if there are persons who perceive intense and long-lasting afterimage after the magenta-to-green fast colour transition compared to their own average values but "weak" and "short" afterimage following a yellow-blue fast colour transition.

K-means clustering analysis (Dervic, 2016; Tan et al., 2006) was performed to detect any further grouping in colour afterimage on normalized subject results ($s_{aftim,\ norm}$ and $t_{aftim,\ norm}$) including each colour change. (Normalization means that we transformed each subject's average s_{aftim} and t_{aftim} results to be 1.0). Each subject's $s_{aftim,norm}$ and $t_{aftim,norm}$ values were transformed to separate nine dimensional vectors (according to the nine colour transitions used in Colour-Colour test series), and cluster analysis of strength and duration of colour afterimage results was run separately. For clustering, we implemented the Apache Commons Math 3.6 API in our Java application developed for test result processing in (Garai, Horvath, 2021; Garai, Horvath, 2022).

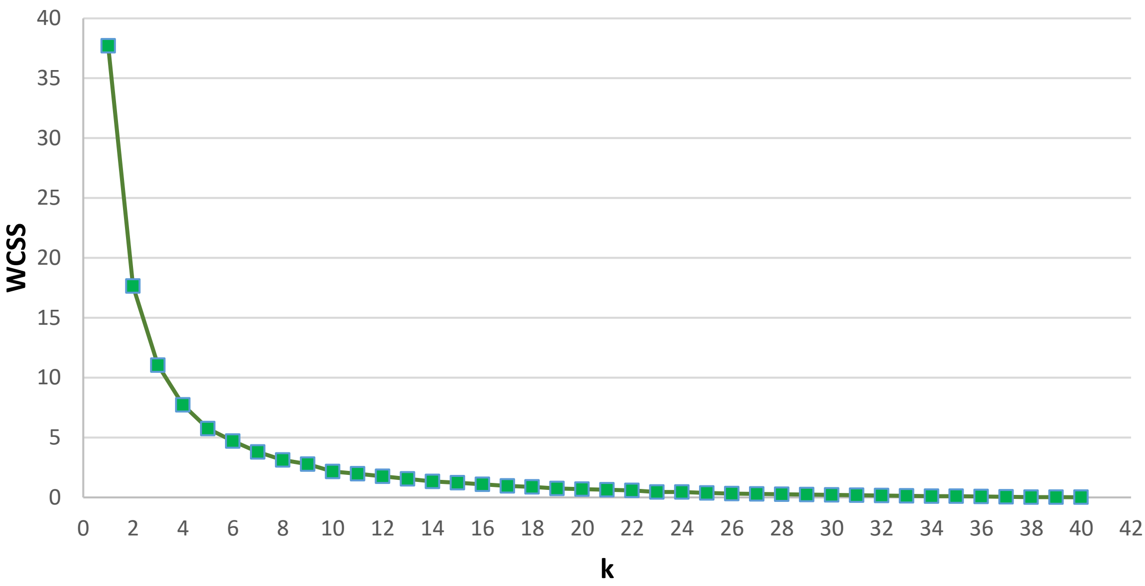
Figure 8: *Cluster analysis of colour afterimage strength: within-cluster sum of squares (WCSS) vs. number of clusters (k).*



Source: *Own work*

Using the elbow method (Figure 8) and some natural criteria, like every cluster should have at least 10 members, 50-75% of males and no centroid has “0” value, we found that the most probable number of afterimage strength clusters is 3.

Figure 9: *Cluster analysis of colour afterimage duration: within-cluster sum of squares (WCSS) vs. number of clusters (k).*



Source: Own work

Using the elbow method (Figure 9) and some natural criteria, like every cluster should have at least 10 members, 50-75% of males and no centroid has “0” value, we found that the most probable number of afterimage duration clusters is 2, and the case of 3 clusters has to be also considered.

Table 1 shows the centroid vectors of the three clusters. Two strength groups, Cluster 1 and Cluster 2 differ by particularly high sensitivity of B2R2→G transition (magenta to green) and particularly low sensitivity of the *opposite* G→B2R2 change. The third intensity centroid does not contain any outlier.

Regarding the duration of colour afterimage at k=2, Cluster 1 shows particularly high afterimage duration of B→R2G2 while the opposite change in Cluster 2 is not particularly low. Instead, particularly long duration was found at B→G colour transition. In the case of k = 3, two duration groups, Cluster 1 and Cluster 3 differ by particularly short duration of G2B2→R and particularly long duration of R→G2B2 at Cluster 1 and particularly long duration of B→R2G2 at Cluster 3.

Table 1: *Cluster analysis – centroids of strength and duration.*

Strength									
k = 3									
Centroid	B →R2G2	B→G	G2B2→R	G1B3→R	B2R2→G	R →G2B2	R→G	R2G2→B	G→B2R2
Cluster 1	1.016	1.250	1.394	1.200	0.933	0.887	0.926	0.798	**0.595**
Cluster 2	1.051	1.206	0.638	0.820	**1.401**	0.938	1.178	0.597	1.170
Cluster 3	1.269	1.360	0.897	0.936	1.177	0.789	0.688	0.958	0.926
Duration									
k = 2									
	B→R2G2	B→G	G2B2→R	G1B3→R	B2R2→G	R →G2B2	R→G	R2G2→B	G→B2R2
Cluster 1	**1.430**	0.978	0.826	0.779	0.811	1.328	0.965	0.788	1.097
Cluster 2	1.120	**1.508**	0.948	1.068	0.907	1.025	0.758	0.743	0.924
k = 3									
	B→R2G2	B→G	G2B2→R	G1B3→R	B2R2→G	R →G2B2	R→G	R2G2→B	G→B2R2
Cluster 1	1.168	1.297	**0.552**	0.657	1.105	**1.525**	0.844	0.872	0.981
Cluster 2	1.203	1.389	1.035	1.064	0.731	1.118	0.768	0.668	1.024
Cluster 3	**1.606**	0.812	1.009	0.971	0.830	0.787	1.121	0.858	1.006

Source: *Own work*

We can conclude that Cluster 3 at strength and Cluster 2 at duration (k=3) represent an ‘average group’. In the other clusters, B2R2→G (magenta to green) and G→B2R2 (green to magenta) differ from the average afterimage strength. It means that magenta-green and green-magenta transition afterimage depends on a personal characteristic parameter regarding afterimage strength. Regarding afterimage duration, B→R2G2 (blue to olive green), R→G2B2 (red to turquoise) and G2B2→R (turquoise to red) differ from the average afterimage duration, and these transition afterimage parameters can be a personal characteristic parameter. This raised importance of magenta-green transition at strength and red to turquoise transition at duration is plausible, but the number of tests (41 persons) should be increased to get a final conclusion.

Conclusion

Our experiments showed that the duration time of afterimage decreases with age in the range of 20–61 years. The difference is highly significant: test subjects in the 20–29-year group perceived the afterimage duration to be more than two times as long as the members of the 50–61-year-old group in both Colour-Colour and Colour-Grey experiments.

Based on this significant difference we plan to perform experiments with different view angles. We also plan to study the ΔC and ΔE-dependence of afterimage parameters. There were no significant differences between the two genders even if we combined the grouping by genders with the age groups.

We presented at high statistical significance that the afterimage duration and strength score have a monotonous dependence for moderately strong transitions (colour-grey transitions, $\Delta L^*=0$ and $\Delta C<100$) but independent on ΔC, ΔE in the case of strong colour-colour transitions ($\Delta E^*>120$). The colour dependence of the afterimage parameters was also examined. We found that there are transitions where the difference between older and younger test subjects is larger than the average, and there are colour transition directions where the duration and strength averages are significantly higher than that of the opposite transitions.

Cluster analysis suggested a plausible conjecture that in every age ranges there are persons who perceive the purple-green transition afterimages stronger or weaker than the average, which can indicate a biological feature.

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