How can color perception be improved for people with color vision deficiencies?

Almost four million people suffer from some sort of color blindness

Everyone knows what a relief it is for someone wearing corrective glasses to suddenly be able to see clearly again, or for someone with a hearing aid suddenly to be able to hear properly again. But can color blindness be improved in a similar way? *By Sascha Ruschenburg, Heike Steinmüller and Erich Kasten*

In addition to color blindness from birth, due to a lack of corresponding cones in the eye, color blindness may also occur later on, e.g. caused by degenerative diseases of the retina or optic nerve. Recognizing colors is one of the most important aspects of visual perception; however, red-green visual impairment or color blindness affects about 9% of all men and about 0.8% of women. In Germany, this amounts to about 3.5 million men and over 300,000 women who would benefit if color perception could be improved. For these people, the act of seeing is a source of constant stress, as the brain tries to extract as much information as possible from inadequate color perception. This is exhausting, comparable to a person with impaired hearing who only understands half of what is being said and has to deduce the rest. As with a hearing disorder, poor vision has a long-term effect on the brain, one becomes tired more easily, more exhausted and prone to frequent headaches.

One of the best-known early studies on how to improve color perception was published in 1997 by Dr. David Harris. Based on this, as early as 2002 Sascha Ruschenburg began to document initial efforts to correct color perception in color-impaired people with dyslexia in studies using "ChromaGen" with positive effects. In 2015, Ruschenburg conducted another study in collaboration with Prof. Dr. Erich Kasten (Medical School Hamburg) and optometrist Sylvia Hergert, which showed that correcting color perception in a group of people with proven color impairment had a positive impact on the frequency and severity of migraine attacks when they were provided with specially adapted colored spectacle lenses.

Pilot finally allowed to fly internationally

Anecdotally, the story of the following patient prompted the authors of this article to look more closely at the topic of improving color perception. Sascha Ruschenburg reported, "In 2017 I received a call from a pilot. He had a German pilot's license which allowed him to fly within Germany. However he was very slightly color blind which prevented him getting an international pilot's license. We were able to correct his color vision using specially prescribed tinted spectacle lenses, which led to his being granted his international pilot's license provided he wore this corrective aid. About a year later, the patient came in for a checkup, and lo-and-behold his color perception had improved over time! A re-examination by the international flight authority confirmed this finding and the pilot received his license, this time without any additional conditions attached. His perception of color is now so good that he no longer needs color correction to fly internationally!"

Do tinted glasses really improve color perception?

Our next step was to check whether the effect found in the pilot could also be demonstrated in other people who had participated in previous studies: Does wearing spectacle lenses that enhance color perception improve the brain's ability to process colors in general, i.e. even without the visual aid? A follow-up study (with additional data acquisition) yielded 11 datasets. These patients initially had an average color recognition without corrective aids of 5.9 plates in the Ishihara color test and an average color recognition without corrective aids of 12.6 plates at the follow-up stage after about a year. This represents a significant improvement by a good factor of two. However, the Ishihara test is subject to a learning effect and in this study the Farnsworth test, which can reveal color recognition weaknesses much more sensitively, was not yet included. Based on these initial results, a study was now planned under more rigorous conditions. The aim was to determine whether color vision can be corrected and whether it could even be improved in a long term without glasses, and thus be learnable?

For the study, 24 participants were found, with ages ranging from 18 to 76 years old. In talking to the participants, it soon became clear that most of them were fairly skeptical about any attempt to improve their color perception. This may also explain the low number of volunteers willing to take part – in accordance with Christian Morgenstern's principle, "that which must not, cannot be" – it is considered that color perception cannot be corrected, let alone learnt.

From the initial questionnaire for the study, it was evident that a deficit in color perception of those affected led to numerous disadvantages in their daily lives. Many spoke of hazards in road traffic,

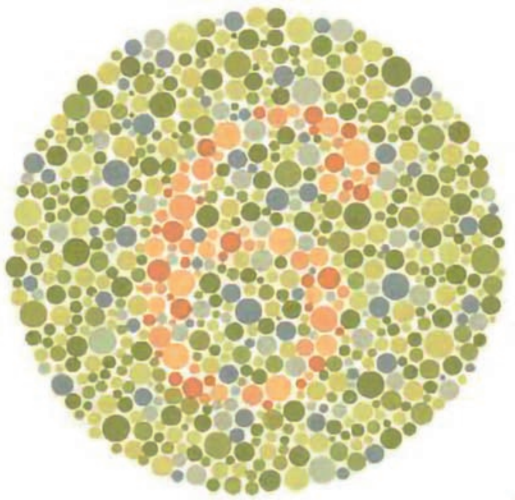


Fig. 1: *Example of an Ishihara plate. People with unimpaired color vision recognize a 6, while people with impaired red-green recognition do not see anything.*

Fig. 2: *Farnsworth color test (15 tile version). The 15 tiles have to be arranged in the correct order.*

for example, due to not seeing red cars against a green background, others talked of disadvantages in their professional lives, due to an inability to understand colored images. Laser pointers during lectures didn't show up against a green background, a draftsman had to have drawings specially made for him so he could read them. But even small things, such as playing "Uno" with one's children or choosing clothes which didn't 'clash', proved difficult too.

In the initial examination of the 24 participants, after the socio-demographic data had been collected, their current color perception was tested by means of the book version of the Ishihara plates (see Fig. 1) and then using a Farnsworth test (see Fig 2.). For the Ishihara test, only spontaneous recognition of the plates was counted as correct; with the Farnsworth test, subjects were allowed three minutes to sort the color plates in the correct order. None of the participants were completely color blind, however all had significant color recognition deficiencies.

256 instead of 16 tints due to two lenses

Following the initial examination, color vision correction was performed by trying 16 different colored lenses. First, the non-dominant eye was corrected using the lens perceived as optimal from the range of 16 lenses available. Then the dominant eye (leading eye) was corrected in the same way. After the dominant eye had been fitted, the non-dominant eye was then corrected again in order to improve color perception further. Finally, a similar procedure was followed again on the dominant eye. This resulted in a combination of two of the 16 possible colors for each eye (see Fig. 3). By combining two colored lenses in each case, the spectrum of different shades for individual adaptation was increased from 16 to 256 possible tints.

After optimal correction of both eyes, both color tests were repeated. On average and across all participants, with the color vision aid, the Ishihara test now showed an improvement from originally 22.1% correctly recognized tasks to 62.1% (two-sided t-test for dependent samples $p<0.00$, i.e. highly significant); and in the Farnsworth test a change in the correct arrangement of the color plates from originally 55.0% to 70.8% (t-test: $p=0.004$; highly significant). This corresponds to a 40% improvement in color discernment for the Ishihara and over 15% for the

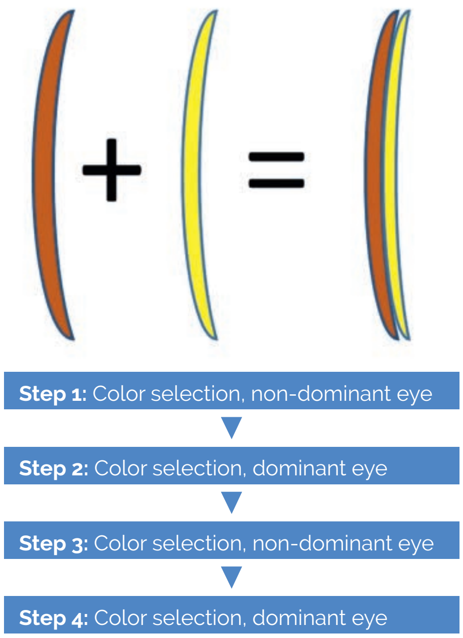


Fig. 3a (left): *Using 16 differently tinted lenses, color perception was systematically varied until the patient felt an improvement in color perception in both eyes. The final lens was then composed of two colors (first and second preference). Steps: Order of examination.*
Fig. 3b (right): *The lenses used for testing and customized patient fitting.*

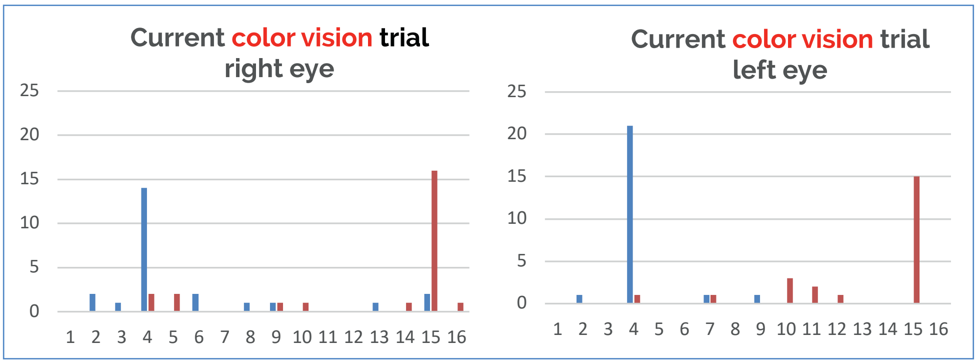


Fig. 4: *Comparison of the color selection of the lenses. The current study showed a preference for colors No. 4 and 15. Blue always indicates the color of the first choice of lens, orange always identifies the lens that was chosen second.*

Farnsworth test. Participants reported better color discernment with the Farnsworth test, based on the difference in brightness of the colored dots, apparently making it easier for the participants to do better in the test.

The evaluation of the lens tints with which the participants were better able to identify colors showed a clear trend: Tint No. 4 was chosen most frequently (14x for the right eye and 21x for the left eye), with tint No. 15 the second most frequently chosen (16x for the right eye and 15x for the left eye). The follow-up examination also concurred with this result.

Thus, a clear preference could be established in the area of color vision correction!

However, this does not hold true for corrections relating to migraine or dyslexia (see Fig. 5). In such cases, there is a need for further research to determine whether standardized lens colors can be offered for specific disorders.

The question that was posed at the beginning of the study was whether individually manufactured tinted lenses can improve vision. It turned out that the majority of the participants favored certain colors. This led to the question: Can a standardized pair of glasses be obtained from the two primary colors, and what benefit would these glasses provide compared to customized glasses?

The trial with a standardized version was now included in the study based on this data collected, and then compared with the customized version at the end of the study.

The placebo control study with 24 study participants with poor color recognition

After the initial examination was performed, the spectacle lenses were produced. Spectacle frames specially designed for the study were fitted. Participants who were already spectacle wearers were fitted with an attachment system (clip-ons). All participants received glasses, but only 50% received the actual prescription. The remaining 50% received placebo glasses or clip-ons with a standard tint of 30% gray or brown. Treatment of the experimental and control groups in parallel was carried out according to age and color perception in line with Ishihara, i.e. always two subjects of roughly the same age and color perception ability were compared. Of these, one was randomly assigned to the experimental group and the other to the control group. The glasses (experimental or placebo) were then given to the patients for daily use. Prerequisite was that the glasses had to be worn for at least three hours a day. This was recorded by the participants. An intermediate examination then was performed after six weeks (see Table 1).

Using the true correction, the Ishihara test showed a highly significant difference in the condition without corrective device between the first and second examination ($p<0.00$ in the two-sided t-test for dependent samples), whereas the slight difference for the Farnsworth test was relatively insignificant ($p=0.82$). The mean difference of improvement between the first and second measurement in the Ishihara test without corrective lenses was 12.5 for the experimental group and 9.17 for the control group; the difference between the two groups was insignificant (two-sided

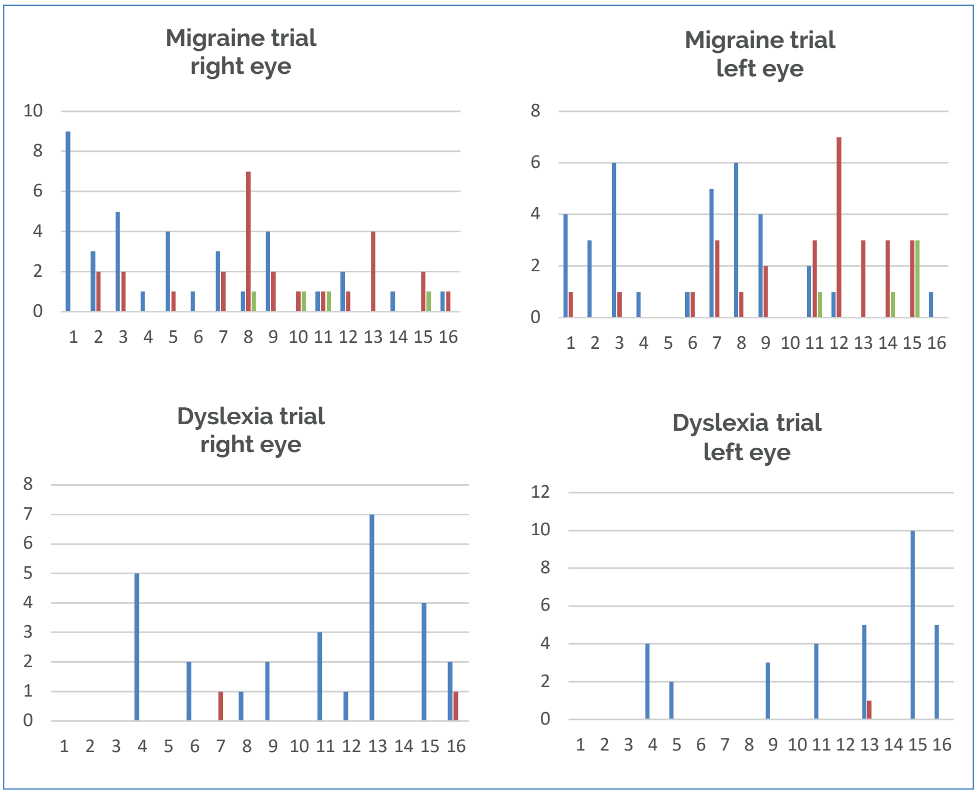


Fig. 5: *By contrast, in the study on migraines (top row) and on dyslexia (bottom row), the choice of optimal lenses was distributed in a much more colorful way (blue = first choice, orange = second choice of tinted lens).*

	Preliminary examination without lenses	Intermediate examination without lenses	Intermediate examination with lenses or placebo
Ishihara experimental group	22.1%	34.6% (+12.5%)	58.3% (+36.2%)
Ishihara control group	22.1%	31.3% (+9.2%)	35.8% (+13.7%)
Farnsworth experimental group	65.0%	66.9% (+1.9%)	66.9% (+1.9%)
Farnsworth control group	45.4%	49.6% (+4.2%)	42.4% (-3.0%)

Tab. 1: *Comparison of initial and interim examination (after 6 weeks) in 24 patients with color vision deficiency (values in parentheses = change compared to initial examination).*

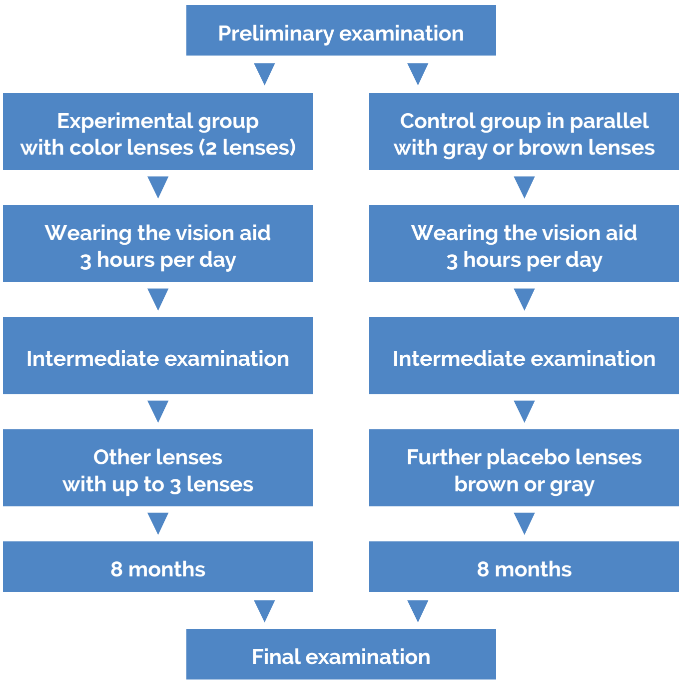
	Intermediate examination with 2 lenses or with placebo	Intermediate examination with optimized lens (no placebo lenses)
Ishihara experimental group	58.3%	70.8% (+12.5%)
Ishihara control group	35.8%	63.3% (+27.5%)
Farnsworth experimental group	66.9%	78.9% (+12.0%)
Farnsworth control group	49.1%	61.4% (+12.3%)

Tab. 2: *Comparison of the interim examination of 24 patients with color vision deficiency with the original lenses (2-fold glazing or gray/brown placebo lens) and an interim examination in which all patients were to perform the tests with an optimized lens (i.e., only colored and no gray/brown placebo lens). (Values in parentheses = change compared to the initial examination).*

t-test for independent samples p=0.27). There was also no significant change in the scores between the experimental and control groups for the Farnsworth test (p=0.27).

Subsequently, both groups were examined again thoroughly by the Ishihara and Farnsworth tests using colored corrective lenses. Here again, the control group showed a significant improvement in performance (see Table 2).

A further correction optimization was then carried out in the experimental group, with this group receiving lenses consisting of up to three different colors. This allowed even better fitting, because now 16x16x16 colors could be combined, i.e. theoretically over 4,000 tints were now available for the customized fitting. Participants from the control group



Course of the trial

also received new placebo lenses – for this, the gray lenses were swapped for brown ones and vice versa.

A final examination was performed after eight months. Unfortunately, at this time four participants were no longer available, had moved away or had not worn the corrective lenses often enough. Thus the number of participants was reduced to 20. Overall, both groups, i.e. also the control group, showed an improvement in color perception according to the examinations carried out. However, whereas the experimental group had improved significantly by the time of the last examination, the control group remained approximately the same, especially in the Farnsworth test (see Table 3). We can only hazard a guess as to why the control group also experienced an improvement based on their statements. Some placebo recipients reported "better detail vision" or "one is clearly more aware of the colors". A strong focus on colors could also have led to a slight improvement in color perception.

The difference between the initial and final examinations is highly significant for the Ishihara test without corrective lenses (p=0.0007 for the t-test for dependent samples); however, no significant difference was found for the Farnsworth test (p=0m20).

The statistical comparison of the difference between the initial and final examinations showed a significant difference in the Ishihara test without corrective lenses between the experimental and the control group (p=0.03 in the two-sided t-test for independent groups). However, this difference was not significant for the Farnsworth test (p=0.29).

One participant saw a colorful rainbow for the first time

In addition to the test data, however, many subjective statements by the participants at the end of the study also supported the fact that there had indeed been an improvement in the perception of colors: One participant in the control group reported being suddenly able to see a colorful rainbow for the first time while still in the first few months of use, even without

	Intermediate examination with optimized lens (no placebo lenses)	Final examination with optimized lens (no placebo lenses)
Ishihara experimental group	71.0% (+12%)	77% (+18%)
Ishihara control group	61.5% (-1.5%)	70.5% (+7.3%)
Farnsworth experimental group	80.4% (+7.2%)	90.4% (+17.2%)
Farnsworth control group	61.1% (-3.6%)	59.8% (-4.9%)

Tab. 3: *Comparison of the interim and final examinations of 20 patients with color vision deficiency, in which all patients were to perform the tests with an optimized glass (i.e., only colored and no gray/brown placebo glass). (Values in parentheses = change compared to the initial examination).*

	Final examination with optimized lenses (no placebo lenses)	Final examination with standardized lenses (no placebo lenses)
Ishihara experimental group	77.0% (+31.5%)	61.0% (+15.5%)
Ishihara control group	70.5% (+36.5%)	64.5% (+30.5%)
Farnsworth experimental group	90.4% (+11.0%)	87.0% (+7.7%)
Farnsworth control group	59.8% (+10.1%)	61.8% (+12.1%)

Tab. 4: *Comparison of the final examination on 20 patients with color vision deficiency, in which all patients were to perform the tests with an optimized glass and with a standardized glass (i.e., only colored and no gray/brown placebo glass). (Values in parentheses = change compared to color vision without correction).*

the filter lenses. The colors were more intense and included more colors of the spectrum than he had previously seen. Another control group participant reported that he was more confident in his assessment of colors when playing with the children. One participant felt that he could see the color green better and that it was more saturated; also the colors of LEDs were easier to distinguish. The specifications of the study stipulated that the glasses must be worn at least three hours a day, but no exact upper limit had been specified. One participant stated that he wore his glasses for about six hours a day; this participant also exhibited the highest rate of improvement in the test procedures, thus suggesting that longer wearing periods may lead to faster improvement.

What remains now is the suitability of the standardized design as a possible correction solution. For this purpose, the data collected in the initial examination was used to produce spectacles with a combined tint of colors 4+15, and compare these with the customized correction solution in the final examination.

As a result, it can be stated that even standardized spectacles already offer a possibility of better color perception to those affected by red-green vision deficiencies, even though the customized version offers better options.

Conclusion: Impairments in color perception can be improved!

In the light of this study, impairments in color perception can now be classed as ‘improvable’. Even though none of the participants succeeded in achieving 100% correction (which anyway had not been expected, given the shortness of the study of about eight months), the results showed there was a clear improvement in color recognition, which was also reflected in the subjective statements.

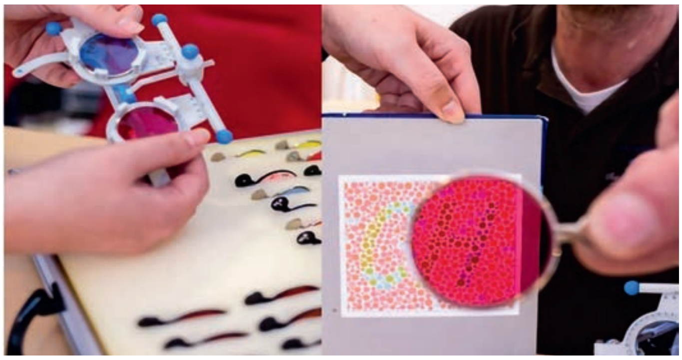


Fig. 6a (left): *Selection and adaptation of the colored lenses to the individual optimum of the patients.* **Fig. 6b (right):** *Example of better recognition of a task from the Ishihara test with the aid of colored lenses. The letter "H", which is otherwise almost invisible to patients with color vision deficiency, shows clearly improved contrast, and can thus be recognized better with the colored lens.*

- Medical examinations in certain professions – where accurate color recognition is indispensable – should be modified in such a way as to recognize that, for those affected, the color recognition rates can be considerably improved with the aid of specifically customized glasses!
- Once classified as having a color-recognition impairment, this should no longer mean that this will remain so forever!
- Irrespective of the superiority of colored lenses over the light 'sunglasses' lenses of the control group, the results of this study prove that deficiencies in color perception should be classified as treatable!

A placebo effect can be largely excluded as the improvement in color recognition using the true correction was visibly higher than the data of the control group. However, the latter group also showed improvements, which may be due to the fact that brown/gray lenses also increase contrast and thus make color differences easier to see. Thus, for further studies, tinted lenses should largely be avoided for the placebo condition, and clear lenses preferred. However, the main difference between the experimental and control group shows that colored glasses are very useful for the purpose of improving color perception.

This is particularly important for children. It would be interesting to know what happens when children suffering from deficiencies in color perception are fitted with such spectacles at an early age. This is illustrated by the following anecdote reported by Ruschenburg:

Back in 2012, Ruschenburg treated a young man who came to him because of a weakness in distinguishing red and green. He wanted to become a sea captain. However, this required a certain ability to distinguish color, which he did not have at the time. Over the years, the young man's prescription was repeatedly adjusted and optimized. In the spring of 2019, Ruschenburg received the news that color proficiency had been sufficiently established that he could now begin his training to become a sea captain. He set out on his first great voyage that same year.

As already stated at the beginning, it is demanding on the brain to have to process a visual impression without or with only weak colors, where especially 'red' and 'green' are difficult to distinguish. As also mentioned at the beginning, this frequently leads to headaches and stress. Such negative effects can be reduced by early treatment, especially in children. Apparently the brain 'learns' to process the colors better at this stage, even without corrective aids. This was also shown in the study by Renjie Li et al in 2009, which demonstrated that contrast vision can be learned and improved through the use of action video games. Which mechanisms are neuro-anatomically and physiologically responsible in this can only be speculated on. Since the number of color-sensitive sensory cells in the retina cannot increase, it is presumably plastic adaptation processes in V4 area of the visual system that now better compensate for the lack of input. The assumption of a brain-related learning process is supported by the fact that the improvement of color perception was achieved over a period of several months.

Finally, for ethical reasons, it should be noted that all participants in the control group were of course given the true correction after completion of the study, and were also offered a follow-up with subsequent optimization, where appropriate! The experimental group was also provided with a new correction, if required, at the end of the study. ◆

Sascha Ruschenburg

Sascha Ruschenburg is a master optometrist; self-employed in Braunfels-Philippstein and Marburg, Germany. The first pilot study on color perception associated with disease patterns was carried out in 2002-2006. A further study on color perception in connection with migraines was carried out in 2016.

Heike Steinmüller

Heike Steinmüller has been a master optometrist since 2017 and is employed at Ruschenburg Optik.

Prof. Dr. Erich Kasten

Prof. Dr. Erich Kasten is a psychologist and neuroscientist. He has worked at the universities of Lübeck, Göttingen and Magdeburg, Germany, among others. Since 2013, he has been an appointed W3 professor of neuroscience at the Medical School in Hamburg, Germany