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**UNDERSTANDING BASIC VISUAL MECHANISMS THROUGH  
VISUAL ILLUSIONS**

**PhD Thesis Booklet**

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## General background and aims

Visual illusions reveal much about the mechanisms of information processing in the visual system. Though the only contact of our visual system with the outer world is the distribution of light projected on our retinas, it builds up a chromatic, 3D model, which makes orientation and action possible. However, our visual system makes certain errors during this process: our perception is often does not correspond to the physical light distribution. During my research, I aim to discover the main characteristics of basic visual mechanisms by means of the systematic investigation of these “errors”, i.e. visual illusions. On the basis of the regularities of these errors, consequences can be drawn with regards to the basic mechanisms of perception. Hereby, as an alternative to physiological experiments, we can gain insight into the working mode of visual system by means of revealing the regularities of psychophysically measurable phenomena and by modelling them. The aim of my research is to investigate the regularities of brightness and colour perception and also the temporal dynamics of monocular and binocular vision by means of psychophysical experiments with visual illusions.

The common feature of brightness illusions is that the perceived brightness relations differ from the physical luminance intensities. Brightness illusions can be divided into contrast and assimilation phenomena. In case of contrast phenomena, the area placed in a bright environment seems darker, while the one surrounded by dark seems brighter. Assimilation phenomena are the opposite: here the grey area in a bright environment seems brighter than that surrounded by dark.

To date, there is no unified model of contrast and assimilation phenomena. Contrast phenomena are traditionally explained by lateral inhibition, according to which within a small retinal area (a ganglion cell’s receptive field), the stimulation of the periphery inhibits the neural response, while the stimulation of the centre enhances it (Baumgartner, 1960). Nonetheless, this explanation is not suitable for assimilation phenomena, since its prediction is the opposite of what is seen. Recent low level explanations (involving early stages of vision), however, still build upon lateral inhibition (e.g. Dakin and Bex, 2003), and some of them extends the model with orientation-selectivity (Blakeslee & McCourt, 2004). Such models convolve the image with filters that are the computer implementation of the lateral inhibition principle, using receptive fields of several sizes (multi-scale models). These convolution models substitute each pixel by a certain weighed sum of its close environment. Mid-level theories (the level which is higher, but not yet conscious), on the other hand, emphasise the role of grouping factors (e.g. Gilchrist, 2006), and the interpretation of the image parts as transparency (e.g. Adelson, 1993) or shadows (Logvinenko, 1999). In the introduction of my thesis, I present new variants of illusions to challenge both convolution-based models and mid-level theories, showing that currently none of them can be considered as an overarching theory of brightness illusions, not to mention veridical brightness perception.

The topic of my first thesis is the refutation of the classical lateral inhibition model by means of presenting new variants of its two traditional textbook demos (Valberg, 2005; Blake

and Sekuler, 2006; Snowden, Thompson and Troscianko, 2006; Goldstein, 2009), the Hermann grid illusion (Hermann, 1870) and the Chevreul illusion (Chevreul, 1839).

In Baumgartner's (1960) explanation of the Hermann grid illusion, he highlights a retinal receptive field that falls on a street section and one that falls on an intersection of the Hermann grid (see e.g. Fig. 3a in Study I). Thus, the inhibitory surround of the receptive field located at the intersection receives twice as much white as the one located in the street section. Therefore, according to Baumgartner's theory, the retinal ganglion cell, whose receptive field is at the intersection, will give a smaller response, since it receives twice as much inhibition as the other. This smaller response manifests itself as a dark spot at each intersection in the perceptual experience.

The explanation is similar in case of the Chevreul illusion: receptive fields located in a step near a lighter neighbour receive more inhibition than those neighbouring a darker step. Thus, the side of each step adjacent to a lighter one will be perceived as darker than its other side (see Study II. for details). The Chevreul illusion has been also included as an additional, clear-cut demonstration of the Baumgartner model in textbooks, which establish the way of thinking of generations of visual scientists

Baumgartner's explanation cannot handle our modified variants of neither classical illusion, although the conditions of the lateral inhibition explanation remained unchanged. Our variants also challenge the modern, multi-scale convolution variants of lateral inhibition models.

The topic of my second thesis is related to the same variants of these classical illusions, by means of which we also attempted to draw consequences on the common explanation for all these classical and novel phenomena. Throughout my thesis, I argue in favour of the filling-in approach (e.g. Cohen & Grossberg, 1984; Geier, 2009) providing illusory phenomena as evidence not only from brightness perception, but also including dynamic illusions and after-effects, discussing how they relate to such a unified theory. The main point of such models is that edges play a crucial role in the perceptual experience, since the areas enclosed by them are filled in by the signals spreading from the edges. Thus the final output image of such models is reproduced from the edge-structure of the input image which corresponds to the human perceptual experience.

However, such a model is required to work with fixed parameters, and it should predict a wide range of phenomena with the same parameter setting. The unified parameter combination is a key issue due to theoretical considerations, since on the phenomenal level seemingly opposite effects are revealed (sometimes the areas surrounded by dark environment, sometimes areas in bright surround seem brighter, and it is unclear to date under which circumstances which phenomenon occurs (Gilchrist, 2006)). However, it cannot be assumed that the nervous system, on recognising the image, would switch from one working mode to the other. It is more plausible to suppose that it uses the same processes when looking at images inducing assimilation or contrast, or when watching real pictures.

Even if one manages to devise a good brightness model that predicts the overall pattern of brightness errors correctly, the question emerges how one can account for illusory

phenomena occurring in the chromatic domain. We attempted to extend Geier's (2009) activation spreading model for chromatic illusions (Hudák and Geier, 2007).

So far, it is only static brightness and colour phenomena that have been mentioned. Investigation such phenomena can reveal the spatial integration of brightness intensities and colour signals in the visual system. Natural stimuli, however, involve temporal changes all the time. Therefore, besides the spatial integration of luminance and hue, the temporal integration of changes is also important to investigate, which is my third topic.

Under some circumstances, static images elicit abrupt illusory changes under eye-movements. Such is the Scintillating grid illusion (Bergen, 1985; Schrauf, Lingelbach, & Wist, 1997), or the impressive rotating and moving patterns designed by Akiyoshi Kitaoka (e.g. Kitaoka and Ashida, 2003). Nonetheless, the most static image that is physically possible to create is the stabilized retinal image. However static physically, it is still subject to perceptual change. Under normal viewing conditions, the eyes make tremors all the time even under rigid fixation. Therefore, the retinal image always moves a little relative to the retina. Retinal stabilization ceases this relative movement. The result is that the image is seen first sharply and clearly for a duration of approximately 1-10 seconds after which the image fades away (Yarbus, 1967; Ditchburn, 1973; Cornsweet, 1974). This means that temporal change at some retinal points is a necessary condition for any perceptual experience to occur at all.

The disappearance of the percept in case of retinal image stabilization clearly supports the role of edges in perception, which favours filling-in model types. If an image contains large homogeneous areas, the brightness and the colour of the homogeneous area is perceived, although no change occurs at that the position under eye-tremor. Eye-tremor can cause temporal changes only at the position of the edges in the image, which indicates that the brightness and the hue of the inner parts of large homogeneous areas must originate from the edges (Cornsweet, 1974). A hypothetical explanation for the above-mentioned dynamic effects elicited by static images may also be related to the high density of sharp edges in those images that elicit abrupt local changes under eye-movements. This might cause some disturbance in the filling-in process.

Visual aftereffects are another class of dynamic illusions in a sense that when the afterimage is perceived, physically no such stimulus is present. This phenomenon is usually attributed to neural adaptation. However, according to a recent review on adaptation by Webster (2011), the definition of adaptation is still unclear. Some of the wide range of the recently known aftereffects also shows the role of edges (e.g. Vergeer, Van Lier and Anstis, 2009; Anstis, 2013 or the McCollough effect described e.g. by Barlow, 1990).

In all the mentioned effects, spatial guidelines, such as orientations and shapes of boundary edges helped the temporal integration of brightness and colour signals. However, the question arises whether the visual system also integrates temporal changes without obvious spatial guidelines. We investigated this issue by eliciting afterimages of unseen shapes, using randomly flickering stimuli to elicit afterimages of meaningful shapes.

The foregoing phenomena work even monocularly. However, to understand the system level it is necessary to investigate binocular vision, too. The two eyes can also be provoked so that the perceptual experience will deviate from what is physically present. Such

a binocular illusion was created by Béla Julesz (Julesz, 1971/2006), known as the Random Dot Stereogram. Although two 2-D random dot images are presented for the two eyes respectively, a 3D image is perceived. The square floating in front of the background is not present physically; it is the visual system that builds up a 3-D model relying merely on binocular disparity, which is the only relevant piece of information that is directly included in the stimulus. This phenomenon proved that the recognition of shapes is not necessary for stereopsis.

However, it is also interesting to study how binocular vision works if the two images do not overlap at all. Surprisingly, the two different images are not merged into one by averaging them, or are not perceived simultaneously adjacent to each other, as could be expected if the visual system were such that it always shows what is physically present. Rather, instead of two static images, one continuously changing dynamic image is perceived. This two-eye illusion is termed binocular rivalry in the literature, since the two images seem to compete to be represented in the actual perceptual experience. The two images are perceived to be constantly alternating, during which the mosaic of the two images are also perceived for some time. Investigating the dynamics of this binocular illusion might reveal important facts on binocular vision. For instance, it had been widely accepted that it is the two eyes that are competing under binocular rivalry, which was believed to take place at a low level in the visual system by the suppression of monocular neurons whose signals originate from the two eyes (e.g. Blake, 1989). However, Kovács, Papathomas, Yang and Fehér (1996) cast doubt on this hypothesis by their patchwork stimuli, suggesting that a meaningful grouping of image parts played an important role in the alternation and not merely the two retinal images competed at a low level. Our results obtained concerning binocular rivalry in children and young adults in Study IV are interpreted in Pastukhov and Braun's (2011) framework, assuming neural adaptation behind bistable perceptual phenomena, which provides a common framework for binocular rivalry and other forms of bistable perception, such as ambiguous figures.

In the light of the foregoing background and our new results, I will discuss the following statements in my thesis and in my related publications:

1. *Modified classical lightness-brightness illusions show that generally accepted local explanatory principles based on lateral inhibition should be rejected.*
2. *Towards a unified theory: brightness illusions show that it is a filling-in mechanism that integrates spatial changes in luminance, in which edges play a crucial role.*
3. *Dynamic illusions and after-images show that the temporal changes in luminance and hue are integrated in time by the visual system even without spatial cues, such as form.*
4. *An illusion for two eyes: binocular rivalry demonstrates that the visual system is capable of integrating merely perceptual temporal changes even without physical ones, which shows differences during the course of development.*

## New scientific results<sup>1</sup>

### Thesis 1.

*Modified classical lightness-brightness illusions show that generally accepted local explanatory principles based on lateral inhibition should be rejected.*

a.) In Study I., we curved the streets of the Hermann grid which made the spots disappear. If the cause of the spots were indeed the larger proportion of lateral inhibition at the intersections, then the same illusory spots should be perceived in the curved grid as in the straight grid, since the stimulation of the corresponding receptive fields projected to the straight and the curved grids is equal. However, no spots are seen in the curved grid.

Therefore, the Baumgartner model, which is merely based on the different stimulation of receptive fields at the intersections and in the street sections, is not tenable. The fact that curvature significantly changes the Hermann grid illusion calls for the rejection of the classical explanation and for developing a new one.

b.) In Study II, we placed the Chevreul staircase in a luminance ramp background so that the staircase itself remained physically unchanged. This modification considerably affected the illusion: it significantly increased or decreased, depending on the progression of the ramp relative to the staircase. When the progression of the staircase was identical with that of the ramp, the illusion was enhanced, whereas when the staircase and the ramp progressed in opposite directions, the illusion ceased. The change in the illusory effect was equally strong through the entire height of each step. In other words, the change of the illusion is not limited to the immediate neighbourhood of the upper and lower edges of the steps, where they adjoin the ramp. This is so, even when any inner point of the staircase far from the ramp is fixated for several seconds.

The theoretical significance of the ramp effect is that it challenges the generally accepted explanation of the Chevreul illusion. In our modified Chevreul illusions, the replacement of the original white background with a luminance ramp background causes physical luminance change exclusively *outside* the area of the staircase, while no physical change has occurred within the staircase. Classical lateral inhibition-based explanations build exclusively upon luminance relations of the steps *within* the staircase. Therefore, if classical lateral inhibition-based explanations were tenable for the Chevreul illusion, then the perception within the steps should not have been changed by the ramp. This explanation, at the best, can predict change merely near the upper and lower boundaries of the staircase, but not through the entire height of the steps. This is in contradiction with the phenomenon that the illusion has changed through the entire vertical height of the staircase merely due to the surrounding luminance ramp. Consequently, it can be concluded that the classical explanation based on lateral inhibition is not tenable for the ramp effect.

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<sup>1</sup> Parts of this chapter will be published in Geier and Hudák (in press).

It still could be reasonable to think that multiscale models can predict the phenomena presented in our images. However, such models fail to predict our double-ramped variants, where a thin inner ramp is included in the original outer ramp, adjacent to the staircase. Although the area of the inner ramp is negligible compared to the outer one, it still dominates perception. The reason for the failure of multiscale models is that the large filters (e.g. in the ODOG model, the largest filter diameter is 36 deg including the surround) are influenced by the outer ramp to such an extent that the outer ramp will dominate the predicted perceptual experience, contradictory to human perception (for a more detailed analysis, see Study II.). In case of the application of small filters only, however, the inner parts of the staircase will not be influenced even by the inner ramp.

Consequently, it can be stated that DoG-based models fail to predict the ramp effect phenomena, since neither small, nor large filters are able to capture these changes, irrespective of whether they are circularly symmetric or elongated.

### **Thesis 2.**

***Towards a unified theory: brightness illusions show that it is a filling-in mechanism that integrates spatial changes in luminance, in which edges play a crucial role.***

a.) In our search for a unified model, we attempted to find the necessary and sufficient conditions of the Hermann grid illusion to occur. For this aim, we applied further distortion types in addition to the sine curves.

Our psychophysical experiments were based on a measure that we introduced as distortion tolerance (Study I.). We defined the term "distortion tolerance" as the amplitude of curvature at which the illusory spots disappear for the particular subject. Our aim was to reveal, by means of empirical data, on what parameters distortion tolerance depended.

Our experimental results demonstrate that higher amplitude of curvature is necessary to eliminate the illusion, when one side of the streets remains straight. On this basis, we concluded that the main cause of the Hermann grid illusion is the straightness of the black /white edges of the streets.

As a unified explanation of the presence of spots in the classical Hermann grid, and their absence in the curved grid, we propose that a diffusion-like activation-spreading (or filling-in) mechanism should be sought behind these phenomena, in which the straightness of the edges is crucial. In Study I, we provided a qualitative description of the model.

b.) If we aim to find a new, unified explanatory principle also for the Chevreul illusions with and without ramps, we have to notice that due to placing the ramp around the staircase, not only the area outside the staircase has changed physically, but the boundary edges of the staircase, too. In Study II, to decide which of these played a more important role in the change of the Chevreul illusion, we placed another, narrow ramp around the staircase, whose direction was opposite to that of the original, larger ramp.

The result of this modification is that although the area of the inner ramp is significantly smaller than that of the outer ramp, the inner one still governs the change in the

Chevreur illusion. If the inner ramp is replaced by a homogeneous rectangle, then the outer ramp has no effect.

This result supports that the upper and lower boundary edges of the staircase control the perceptual experience, and not the area size of the ramp, since such a narrow ramp as half a degree can prevail against the effect of the much larger outer ramp. Therefore, we conclude that it is the boundary edges in the image that govern perceptual experience instead of the large background areas, and long-range interactions should be assumed between edges and the areas enclosed by them.

Thus, the implications of the Hermann grid illusion in Study I and that of the Chevreur illusion in Study II largely overlap both concerning the refutation of their traditional explanations and the role of edges and filling-in in a new, unified theory.

### **Thesis 3.**

***Dynamic illusions and after-images show that the temporal changes in luminance and hue are integrated in time by the visual system even without spatial cues, such as form.***

Besides the investigation of spatial integration of luminance, we also investigated one aspect of temporal integration by means of a novel afterimage. Observers (n=130) were presented with a movie in which a field of randomly coloured or black/white flickering squares were watched for 45 s. A shape of a capital letter was hidden in the display, by means of an implicit bias towards green (or in the achromatic version, towards white). Observers could not perceive this letter. Thus, although only randomly flickering squares were seen, subjects readily reported the pink afterimage subsequently, naming the letter correctly. This demonstrates that the visual system integrates the changing colours over time and stores them. A certain type of adaptation occurs for the average of each retinal point, which results in a recognisable shape in the afterimage, although no coherent shape is present during the adaptational period.

### **Thesis 4.**

***An illusion for two eyes: binocular rivalry demonstrates that the visual system is capable of integrating merely perceptual changes even without physical ones, which shows differences during the course of development.***

Not only physical changes are integrated in time by the visual system, but illusory changes as well. This is well demonstrated under binocular rivalry, where two static images are shown to the subject, however, dynamic illusory changes in the mixture of the two images are perceived.

We investigated this binocular illusion in psychophysical experiments, for which the paradigm was developed in international cooperation (Study IV.). Here subjects were requested to continuously point by a joystick to the image they were seeing at the moment, while their response was recorded by the computer. Hereby the dynamics and the neural adaptational effects behind the phenomenon can be investigated.

We studied binocular rivalry in 9 and 12 year-old and in grown-up populations. (Study IV). Our results are interpreted in Pastukhov and Braun's (2011) framework, assuming that

the visual system integrates the dominance times of the given percept, which influences its future dominance times. Thus the model describes a certain type of neural adaptation behind bistable perceptual phenomena, which was confirmed by our results. We also found significant developmental differences within this framework: children alternated and adapted more quickly and showed a stronger adaptation effect than adults. The developmental curve, however, is incomplete; further investigations on adolescents would seem to be fruitful.

## Conclusions and further directions

Our results refuting the classical lateral inhibition model have already gained international reputation (Anstis 2006, Bach & Poloschek, 2006; Hoffman, 2008; Howe & Livingstone, 2007; Lingelbach & Ehrenstein, 2004; Schiller & Carvey, 2005). We are planning to develop Geier's (2009) filling-in model further to predict all known brightness phenomena. It is indicated by the bunch of evidence enlisted in my thesis that it is the filling-in model type that is most feasible to capture the essence of brightness perception, while convolution-based models seem to meet numerous difficulties. Still, other existing models can only account for a much smaller proportion of illusions and have not been extended to chromatic pictures. Our aim is to modify our chromatic model so that it will capture a wider variety of colour illusions, by means of which we will get closer to understand colour vision. We also aim at further investigating the development of brightness and colour perception as well as stereopsis and binocular rivalry. Furthermore, we plan to explore dynamic phenomena and spatial vision, and capture them by a similarly exact computational model that matches the results of our future psychophysical experiments.

## List of publications related to the theses

### Thesis I.

Geier J., Bernáth L., Hudák M., Séra L. (2008). Straightness as the main factor of the Hermann grid illusion. *Perception*, 37(5), 651 – 665. ([Study I.](#))

Geier J., Hudák M. (2011). Changing the Chevreul Illusion by a Background Luminance Ramp: Lateral Inhibition Fails at Its Traditional Stronghold - A Psychophysical Refutation. *PLoS ONE*, 6(10), e26062. doi:10.1371/journal.pone.0026062 ([Study II.](#))

Geier J., & Hudák, M. (in press). The curved grid non-illusions: eliminating Hermann's spots and Lingelbach's scintillation. In: Todorovic, D. and Shapiro, A. (eds.). *The Oxford Compendium of visual illusions*. London: Oxford University Press.

Geier J., & Hudák, M. (in press). Changing the Chevreul Illusion by a Background Luminance Ramp. In: Todorovic, D. and Shapiro, A. (eds.). *The Oxford Compendium of visual illusions*. London: Oxford University Press.

Geier J., Séra L., Bernáth L., Hudák M. (2006). Increasing and decreasing the Chevreul illusion by a background luminance ramp. *Perception*, 35, ECVP Abstract Supplement

### **Thesis II.**

Geier J., Bernáth L., Hudák M., Séra L. (2008). Straightness as the main factor of the Hermann grid illusion. *Perception*, 37(5), 651 – 665. ([Study I.](#))

Geier J., Hudák M. (2011). Changing the Chevreul Illusion by a Background Luminance Ramp: Lateral Inhibition Fails at Its Traditional Stronghold - A Psychophysical Refutation. *PLoS ONE*, 6(10), e26062. doi:10.1371/journal.pone.0026062 ([Study II.](#))

Geier J., & Hudák, M. (in press). The curved grid non-illusions: eliminating Hermann's spots and Lingelbach's scintillation. In: Todorovic, D. and Shapiro, A. (eds.). *The Oxford Compendium of visual illusions*. London: Oxford University Press.

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Hudak M. & Geier J. (2011). The segmenting effect of diagonal lines in the ramped Chevreul illusion. *Perception*, 40, ECVP Abstract Supplement, 202.

### **Thesis III.**

Anstis S, Geier J, Hudak M. (2012). Afterimages from unseen stimuli. *i-Perception* 3(8) 499–502. ([Study III.](#))

Geier J., Séra L. & Hudák M. (2007). Whiter than white, blacker than black-overshot in lightness perception. *Perception*, 36, ECVP Abstract Supplement.

Hudák M, Geier J. & Lingelbach B. (2010). Scintillation in the Spillmann–Levine grid. *Perception*, 39, ECVP Abstract Supplement, 166.

### **Thesis IV.**

Hudak M., Gervan P., Friedrich B., Pastukhov A., Braun J., Kovacs I. (2011). Increased readiness for adaptation and faster alternation rates under binocular rivalry in children. *Front. Hum. Neurosci.*, 5:128. doi: 10.3389/fnhum.2011.00128 ([Study IV](#))

Hudák M., Jakab Z. & Kovács I. (2013). Phenomenal qualities and the development of perceptual integration. In: Albertazzi, L (ed.). *Handbook of experimental phenomenology: visual perception of shape, space and appearance*. Chichester: John Wiley & Sons Ltd. pp. 145-163.

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