GAA
Gemmological Association of Australia

# The Australian Gemmologist

July – September 2013

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Number 3

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The official journal of The Gemmological Association of Australia

## The Gemmological Association of Australia

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## The Australian Gemmologist

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# The Australian Gemmologist

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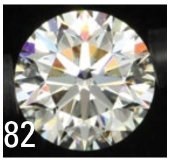
Front Cover Photo: Images of four diamonds are presented as stereo pairs. These images, taken from slightly different angles, replicate what each eye sees and what the brain then merges into one image. Readers are invited to view each stereo pair using the stereo viewer provided with this issue to see single images of each diamond thus demonstrating how our brain processes the image seen by each eye into one new image combining the most interesting details of both views. This issue contains a single important paper by members of the Diamond Cut Research Project who describe how cut diamonds which are attractive to consumers are viewed differently by people from all walks of life pointing out the commercial need to standardise both the measurement and description of cut diamonds.

## Contents



## Foreword

# The Corinne Sutherland Memorial Issue

*Corinne Sutherland (1917 -2013)*


*Corinne Sutherland (1917 -2013)*

It was with great sadness that in June this year we were advised of the passing of Honorary Life Member Corinne Sutherland. Corinne contributed an enormous amount of time and effort to the Gemmological Association of Australia, serving in several different capacities at both Division and Federal level.

Corinne obtained her Diploma in Gemmology in 1960, winning the Lustre Prize for the highest practical result in Australia. In 1967 she gained a distinction in the Diploma in Diamond Technology, and in 1971 she donated the first Sutherland Prize – a copy of Eric Bruton's book *Diamonds* - awarded to Mr Ian Tulloch as the best student in that course. Corinne was made an Honorary Life Member in 1980 in recognition of the significant contribution she made to the Association over many years.

At the 1983 Federal Conference it was resolved that the Sutherland Diamond Award, as it is now called, would be awarded in-perpetuity, with a silver medallion being presented to the student receiving the highest marks with distinction in the Diploma in Diamond Technology course (Brown, 2004).

It is fitting that Corinne is remembered in this issue as it includes an important and innovative article on diamond, the gemstone that Corinne loved the most. The article reports on the extensive investigations of the Diamond Cut Research Project examining just how our perceptions of a diamond's beauty relates to human vision. A measurement system to achieve this is described and will be followed by further work. Interestinglly one of the authors - Mr Garry Holloway was the recipient of the Sutherland Medal in 1985.

It is because of dedicated people like Corinne that the Gemmological Association of Australia enjoys the acclaimed reputation it has today. She will be greatly missed. The Gemmological Association (GAA) extends its deepest sympathy to her family.

Terry Coldham
*Chair Editorial committee*

### Reference

Brown G. (2004) A brief history of the GAA's Diploma in Diamond Technology course. *The Australian Gemmologist*, 22 (3), pp. 91-98.

# Vale Corinne Sutherland

Corinne was a remarkable person with interests in many fields especially the sciences. She attended Melbourne University where she obtained her science degree. During the Second World War, Corinne worked in Research and Development charged with developing foods suitable to be sent to troops serving overseas.

Corinne then travelled to England with her husband Dr Geoffrey Sutherland where she lived and worked for the next few years. After returning to Australia, she was kept busy raising a family and working in the Eye and Ear Hospital in Melbourne with her husband. Corinne, with a renewed interest in the sciences then developed a further interest in gemmology, and applied to the Gemmological Association of Australia (GAA) Victorian Branch (later Division) to do her Diploma in Gemmology. She received the Diploma with the registered number 562.

Through her involvement in the GAA Corinne made many life long friends not only in the Victorian Branch but also throughout Australia.

Corinne entered the jewellery trade in the late 1960's through her friend Julia Myers who owned and operated a gemstone business in Sydney called Affiliated Importers Pty. Ltd. Corinne suggested to Julia that she open an office in Melbourne which Corinne would manage. The office was opened in 1969, and in her management capacity Corinne encouraged and helped staff to complete the GAA Diploma in Gemmology as she believed "to be well educated in your profession was good for the individual and good for the trade".

Corinne had a passion for diamonds. She sat the Diploma in Diamond Technology course in 1967, passing with distinction. Moreover she wanted students in the future who achieved the highest marks to be formally recognized, so she sponsored The Sutherland Prize to be awarded to the best Diamond Technology student in Australia. This was first awarded in 1971. In 1983 it became known as The Sutherland Diamond Award and a special silver medallion was struck to be awarded in-perpetuity to the student gaining the highest marks in Australia providing that he or she attained a distinction.

Corinne wanted to be more involved with the educational side of gemmology so she resigned her position as manager of Affiliated Importers early in 1970 to be able to devote more time to the GAA. She delivered lectures for the Gemmology Diploma course as well as in Diamond Technology. She also took up an invitation to teach basic gemmology to gold and silversmith students at RMIT, some of whom then went on to complete the Diploma in Gemmology.

Corinne loved to travel and loved an adventure. In the 1960's she travelled with her husband to China well before China became open to the western world. Whilst there, Corinne learned about jade and its treatment and cultural history, knowledge which she then shared with her gemmology friends. Over the ensuing years Corinne travelled extensively, usually off the beaten track and if it involved gemmology, all the better.

In the years since Corinne moved on from Affiliated Importers she always kept up an interest in the Melbourne office and this is where I was to meet her in 1973 when I commenced work there as a "junior". I did not realize then how fortunate I was to meet Corinne Sutherland. She became a friend and mentor for the next 40 years.

Corinne returned to work at Affiliated in the mid 80's, and by then she had become an "institution". People from all parts of the industry would seek her out for all sorts of advice. Corinne was widely respected within the Gemmological Association of Australia and made many great and life long friends which she cherished. All her gemmological friends and members of the Australian gemstone and jewellery industry will miss her greatly.

The Gemmological Association of Australia recognized Corinne's contribution to the association over many years by making her an Honorary Life Member in 1980. I know she was very proud of this. Corinne retired from Affiliated Importers in 1990 but only from "the office", she still kept up her Gemmology with continued reading and gathering of information. New information and technologies in gemmology always excited her and as had always been the case, she loved to share this information.

Corinne Sutherland was an extraordinary person who has left us all a great legacy in one of her favourite sayings:

*Be passionate about your interests and then "just get on with it."*

Christine Diorietes FGAA

# My Memories of Corinne Sutherland

From my very first Federal Conference in 1980, there were a few individuals that stood out as being larger than life - Geoff Tombs, Mary Durbridge, Pat Callaway, Cec Stott and Corinne Sutherland. It was clear to me even at that early stage with my involvement in the GAA that nothing got past those gate keepers. There is no doubt that the reputation and prestige that the GAA enjoys today is in great part to the efforts of Corinne. She was very brilliant and very strong willed.

I still clearly remember the conference in the hills of Hobart where these five were in the hotel room with a large bottle of Johnnie Walker looking over the agenda items for the next day and in effect deciding the outcomes there and then. The meetings were a mere formality.

Corinne was very involved with the development of the Diploma in Diamond Technology course. It was the part of the GAA's studies in which she took a keen interest till her death. She designed and donated the Sutherland medal which is still the highest award that we give for this course. A few years back we looked at standardising all the medals of the GAA. We changed the design and size of the Sutherland medal. In my then capacity as Chairman of the Association, I got a phone call from Corinne who in no uncertain words informed me that the Sutherland medal will not be changed. What was I to do? There was no way I was going to cross swords with one of our most esteemed Honorary Life Members. So even though we did have a uniform design for all the other medals, the Sutherland medal remained as it was and as it is today.

I, like so many other gemmologists had many dealings with Corinne on a professional capacity at Affiliated Importers. We always chatted about this issue and that issue in the GAA.

I still remember her smiling and patting me on the back when I became a member of the Royal Society of Victoria.

As life would have it, my eldest daughter Rickie went to school with Corinne's granddaughter Allie. Through this connection I still had a loose contact with Corinne after she had withdrawn from active participation in the GAA. Even so, Corinne's love for the GAA never waned.

It was no secret that in the twilight of her life she became very frail. Though her body was collapsing around her, her mind was as sharp as ever. At one point the Honorary Life members decided to write a joint letter to the Federal Council regarding an issue and I rang Corinne to see if she was willing to put her name to it. Though not having been involved with Council issues for some time, she insisted on being brought up to speed and more importantly being kept in the loop. Her contributions to the debate were still very pertinent and lucid. But leaving the administration of the GAA aside, Corinne loved gemmology. She loved her diamonds and treasured the ring that was set with natural Type 2 blue diamonds. The GAA is the poorer for losing such a visionary and contributor. Her shoes will be hard to fill.

On behalf of my family I wish to pass on our deepest sympathies to Corinne's family.

Corinne, I bow my head and lower my loupe to you.

Ronnie Bauer FGAA, Dip DT
*Federal Secretary*

# How diamond performance attributes: Brilliance, Scintillation and Fire depend on human vision features

Sergey Sivovolenko, Yuri Shelementiev, Garry Holloway, Janak Mistry, Roman Serov, Stepan Zhulin, Kristina Zipa

## Abstract

This study describes how visual properties determine the perception of a diamond's appearance and its performance attributes of brilliance, scintillation and fire, and how these influence beauty. Further articles will describe other parts of our cut study project. This research enables the development of methods and instruments for diamond performance analyses, shifting from current diamond cut rejection based tools, to diamond performance scoring systems, and the introduction of a new consumer language for communication between diamond buyers and sellers. The proposed Performance Scoring System is consumer friendly and can be used to design and manufacture new diamond cuts with improved optical appearance.



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## 1. Introduction

### *Overview of the Diamond Cut Research Project*

This article is the first in a series on the on-going Diamond Cut Research Project (DCRP). Founded in 1998, the DCRP aims to improve diamond cutting and cut analysis and to support the market that lately has been continuously losing market share and consumer confidence to other luxury products. Engagement ring sales' (and sales of diamonds in general) as a share of discretionary spending has been reduced in recent times.

Intermediate results of the DCRP enabled our team, to create a new fancy cut in 2008 with the appearance and performance (as perceived by end users) as equal to a standard round brilliant cut of the same visible size. In other words, to develop a new diamond cut that would be preferred to a round cut with the same face up area.

This is a worthwhile goal because a high-performance fancy cut could potentially open up a new era in the culture of diamond consumption. Where the current choices are largely high-class "classics", we envisage consumers having the choice to appreciate other genres, such as "jazz", "rock", "folk" and "punk", to use music as an analogy. This allows a diamond's unique selling point to step beyond its current restricted value, based mainly on natural rarity with a small component of value-added craftsmanship. The potential for craftsmanship to add overwhelming value by creating a beautiful appearance and outstanding optical performance via cutting would be comparable with the difference between Swiss timepieces and ordinary watches.

Fundamentally the challenge is not limited to the technological development of outperforming fancy cuts. It should be supported by an adequate means of sale. A balanced, user-friendly and intuitively understandable language for consumer-seller dialog is a critical point.

When consumers are judging the difference in performance of two diamonds being considered for purchase, it is beneficial for manufacturers to have the opportunity to gain the information that can help them respond to end users' desires and preferences in the design and development of new cuts. This will encourage consumers to engage and become involved because 'we all like to know that our votes (or dollars) count'.

From this perspective, the DCRP will establish the opportunity for a new start in the relationship between diamond industry stakeholders with a new competitive and sustainable market, based on scientific development and understanding of the appearance of diamond and the attributes of its cut.

The three most important appearance attributes of diamonds are commonly held to be brilliance, scintillation and fire. Together, we refer to these attributes as Performance. We also use the term Beauty in our next articles, while in the trade the term Life may be used, a term that also occurs in earlier literature. In our view, these two terms, as well as Diamond Performance are synonymous. We draw no distinction between them within the scope of this article, and hence the term Performance is used.

## Research problems

We faced the problems of different people - specialists and end users alike - each articulating diversely different evaluation and descriptions when comparing two diamonds. We break these differences into repeatability, precision and manufacturing problems as discussed below.

- Repeatability in polished diamond evaluation:
  - It is impossible for different people to concurrently discuss the same flashes or patterns in a diamond when each sees a different picture, in varying lighting conditions, viewing distances and directions. It is impossible to repeat the viewing position for one observer of a diamond to the next, i.e. both see different pictures.
  - Communication even between diamond experts is frequently discordant because some phenomena are construed differently, especially brilliance, scintillation and fire. During our project to develop objective scoring or metrics systems (which will be discussed in detail in a future article) for the evaluation of these subjective phenomena, brilliance, scintillation and fire we faced the problem of the absence of suitable definitions for those attributes. That led us to try to determine what these phenomena actually are, and the factors that influence them. We concluded that these processes and visual properties are very important for these phenomena.
  - Every individual has their own understanding of what a big or small sparkle or flash is, what a bright or intense flash is.
- Precision in polished diamond cut evaluation:
  - For an individual to make a precise evaluation of a diamond shown to them there is a level of competence and experience required for an accurate assessment, just as there is for perfume testers or wine judges. Flashes in a diamond emerge, change and disappear so quickly that, while the eye sees them, the brain is not able to give a proper evaluation without the skill to judge the phenomena. To perform an evaluation a person should view the same phenomenon many times in a reproducible environment. Only then can the brain properly evaluate the phenomenon.
- Problems with manufacturing:
  - Another problem arose in that new computer designed diamond cuts were difficult for cutting facilities to reproduce. Faceted diamonds deviate in geometrical parameters, performance and metrics from those initially planned and predicted.
  - The precision and results of (our) trial manufactured diamonds differ significantly from the plan in the first examples; some facets had deviations of up to 2 degrees. High precision was only achievable in round cuts, and only then for state of the art facilities. There was no technique available to enable fancy shape cutting to a precision of 0.2 to 0.5 degrees. Part of the problem was the production of an arbitrary girdle shape. Even minor (invisible to the eye) deviations in the girdle shape resulted in larger facet azimuth or slope angle errors. A small facet slope angle variation altered performance dramatically. Moreover different diamond sizes required different facet patterns to maintain the optimum size of virtual facets. To produce a new cut with a fixed shape, proportions and a pre-set size made it difficult to cost effectively select diamond rough.
- While expert assessment is essential, consumer language is also necessary and important.
- Intellectual property (IP) protection adds greatly to the complexity, duration and costliness of such research work because some contract manufacturers may be inclined to attempt to copy and reproduce the designs.

## Goals

To solve the above problems, we set the following goals:

- Repeatability of evaluation:
  - Create a consistent environment, meaning that different specialists (experts in the field) and consumers can see diamonds under the same conditions.
  - Definitions of phenomena must be unambiguous and complete so that all specialists evaluate the same phenomena equally.
  - And, if each consumer is asked the same set of questions, to ensure that those consumers look at the product (diamond) under similar conditions and construe the phenomena they see in a similar way so that a reasonably representative response is received.
- Precision in polished diamond cut evaluation:
  - Design tools to get an exact evaluation of the performance of an arbitrary cut in the same coordinates by individuals or a large number of specialists (say a group of 20 or more, including those located in different cities and countries), and to enable comparison of pairs of different diamonds, with each in the same lighting and viewing environment.
  - Design and develop metrics for performance evaluation allowing for human psychophysiological features of perception of a diamond. Discover differences between an evaluation based on metrics and that provided by human subjectivity. Establish methods to account for any variance in human evaluation and metrics so as to not block the goal of developing new high-performance cuts.
  - Reduce the time and expense in polling or surveying specialists and consumers.
- Problems with manufacturing:
  - Develop manufacturing tools and techniques and enable the cutting and polishing of diamonds to precisely reproduce the computer predicted proportions and angles of new cuts.
  - Reduce the number of diamonds wasted in the search for new cuts (as diamond rough material is expensive).
- Develop consumer language and sales technologies based on consumer understanding, awareness and language.
- Solve the IP protection problem. (This goal is beyond the scope of this series of articles).

## *Content of each article*

**This first article** is mainly devoted to Diamond Cut Research problems, especially the repeatability of diamond cut evaluation. For this purpose the paper deals with describing the relevant important properties of human vision and how these properties determine key phenomena such as brilliance, scintillation and fire. Technical definitions of brilliance, scintillation and fire are introduced. The actual creation of the objective metrics based on these definitions is a complex continuously evolving process, rather like the history of map making - that is a process that may last a long time. However, it is important to expedite the interaction between consumers, sellers and producers within a research frame, so that the market can start making effective use of the research results immediately and increase the industry's competitiveness, develop confidence and bring creativity and innovation into the diamond sales system. Consumer-seller interactions happen in the thousands every day, and each interaction could immediately add value to the industry if the information was captured and included into the research frame.

In order to justify this approach to diamond Performance metrics development and provide the precedent that processes like this are successful in other areas of human activity, we compare the development of cut assessment systems with the history of how geographical maps were developed (see map analogy below). This analogy will enable the diamond market stakeholders to appreciate the aim of the development of diamond Performance metrics and the prospect of using similar processes in the development of the diamond market.

The **second article** describes problems and solutions in the precision of polished diamond cut evaluation. It considers the example of applying the research to create new high performance diamonds (titled Process Flow) and the tools developed for assessing performance based on both 3D diamond models and real diamonds. New key concepts such as ETAS (effective total angular size), virtual facets and fire metrics are established.

The **third article** introduces examples of performance reports, sellers' information and buyers' communication patterns including initial suggestions for a consumer language model, methods of receiving opinion data from consumers for a large number of cuts (analogous to creating geographical maps based on a vast numbers of small measurements, or crowd sourcing). A method of creating objective precise beauty and performance maps based on a large number of subjective human and consumer assessments and choices will be presented. Development of objective metrics is discussed and demonstration of the importance of using relative and absolute metrics simultaneously as exemplified by comparing fire and brilliance for 0.20ct, 1.00ct, 20.00ct diamonds of the same cut and identical proportions is featured.

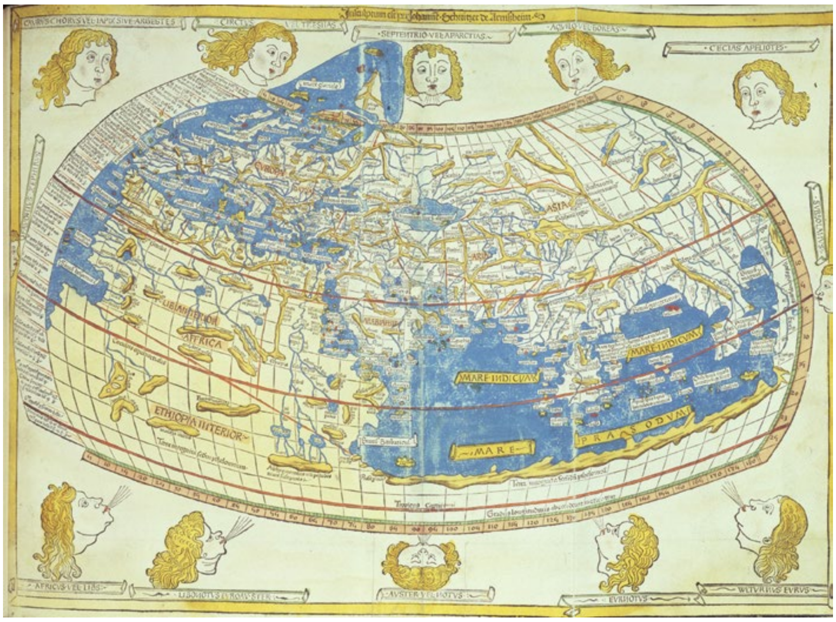



*Figure 1.1 Ptolemy's world map*

## *Mapping a diamond*

In certain respects, the development of high-performance diamond cuts is not unlike the progress of cartography. A combination of ongoing field reports, more sophisticated measuring tools and better scientific understanding led to ever-better maps. Diamond cut design is similar.

In diamond cut evaluation we are at the stage of more or less an accurate map created on the basis of many separate measurements, which describe the standard round cut. However, this cut was devised using approximately the same methods, and with similar inaccuracy – viewed on current standards, as when Ptolemy's map of Italy was created (Fig.1.1).

When saying 'measurement', we do not mean the actual measurement of a diamond's facet angles. We mean which of the different round cuts that have been created is 'better' for the observer when looked at in a comparable situation? The evolution of diamond cut creation and the comparison or 'measurement' of thousands of round cut diamonds led the diamond industry to understand how to make the round cut performance better over time. For any other fancy cut the number of such 'measurements' is substantially lower so the potential area of fancy cuts is less well mapped (described).

Developing similar 'local maps' for each new diamond cut will take many years. Yet it will not be possible presently to establish a global map for each cut type. The reason for this is that we have neither a common basis (latitude and longitude) when describing cuts, nor a method of 'distance measurement' between different cuts, just as previously there was a problem of distance measurement between continents without precise chronometers, radio, GPS and satellite photography. In the diamond case, the question posed is how to compare a princess to a round brilliant, or make comparison between an emerald cut or any other step cut, to a radial style brilliant cut? But if we introduce a common standard, it is possible to use the most contemporary method of map creation, i.e. by means of 'crowdsourcing', where several hundred or even thousands of independent measurements are made from different directions in order to have a triangulation prototype for accurate measurements. In other words, the requirement is to perform several comparative measurements based on consumers' observations, for example for the following pairs: oval-pear, pear-round, round-oval, oval-cushion, round-emerald cut etc. These measurements need to be done with the same measurement system, in standardized and synchronized illumination and observation conditions.

What is the basis when talking about cuts? First, it may seem that this is about diamond slope and proportions values, but it is not. We believe it is about consistent and exact definition of brilliance, fire, scintillation respectively, which are equally important, and analogous to latitude and longitude, cardinal directions and common distance measurement in cartography.

The first cartography measurements were mostly observations. "I walked five days from town A to town B. Town B is seven days' walk to the East of town C". Having the coordinates of town A and C, by analysis and comparison of several similar observations and coordinates it was possible then to determine town B's location on a map. The more detailed independent geographical observations the more accurate town B's location. Similarly the invention of more precise measuring instruments, the compass, sextant and theodolite for example, enabled the number of observations to be reduced and those observations were now more accurate. In the diamond case there is no device for measuring brilliance, scintillation and fire. We can only detail that one diamond has more fire than another. In order to increase the accuracy of diamond beauty maps, instruments for performance measurement should be invented. To do this however requires definitions for brilliance, scintillation and fire to be formulated which must contain a description of their origin mechanism. That is, two types of definitions are required. The first is for consumers, so that they can understand and describe 'what' they observe. The second definition must relate to the observing device, and it should include information 'on' the phenomenon emergence mechanism and the nature of it.

An interesting analogy occurs between maps and diamonds when considering a problem of longitude determination at sea. It was easy to determine latitude with a sextant, but without longitude it was not possible to determine a ship's location. Initially longitude was estimated based on the ship speed and duration of the voyage, but this method was very inaccurate. Later the method of sunrise time difference at the zero meridian and ship location was introduced. In this method the error depended on the accuracy of the chronometer. Therefore, military and marine administrations invested a lot in the invention of precise chronometers and other alternative means of longitude determination. But even after the invention of radio, enabling precise time information, the subjective error caused by knowing the actual moment of sunrise remained a problem of human subjectivity until the development of global positioning systems (GPS).

When considering diamond cut, however there have been accurate methods of facet slope and proportion determination, and even illumination and observation standardization systems, yet still the observer's subjectivity remains. And today the opinion of individual consumers on which diamond is more beautiful remains subjective – a matter of personal preference. In order to create an accurate 'diamond map', which includes all shapes and cuts, a statistically large and significant number of observations and measurements are required and this shortfall has not yet been overcome.

## 2. Background

Before proposing and discussing our findings it is important to list the prior knowledge in the field. Box A includes several authors' definitions and descriptions of brilliance, fire and scintillation. Box B defines our parameters of a round brilliant cut diamond that we use as a reference standard. Below we discuss some of the commonly used and often conflicting terminology that various diamond researchers, buyers and sellers employ. The authors hope that our proposed new definitions based on our studies will simplify, clarify and provide a more accurate basis for future studies and development.

### *"Ideal" and "Super-Ideal" diamond cuts.*

Terms such as 'Ideal cut' and 'Super-Ideal cut' are often used and yet there may be no objective basis or definitions underlying these notions, and at times there is overlapping conflict between terminologies. Even though researchers, informed diamond consumers and laboratories may use these terms, dealers, retailers and end users frequently use quite different language. Common market language relies heavily on terms used on diamond grading reports, such as cut proportion, symmetry and polish grades like Triple Excellent, Excellent, Very Good, XXX, VG, X, VG etc.

Over the past decade the understanding of brilliance, fire and scintillation has been challenged in part by buyers asking more questions about diamond appearance, and in part by manufacturers of 'Ideal' and 'Super-Ideal' cuts, claiming that their products were substantively different or better looking than other mass produced or generic unbranded goods.

Cited below are some statements made by manufacturers and dealers in professional periodicals and in patents:

> "The new OE cut is derived from a formula totally different from Marcel Tolkowsky's ideal proportions…. cuts are engineered in a way that returning light from the diamond focuses on the crown so that the stone gives more brilliance, more scintillation and more dispersion of light than the traditional ideal cut." (K. Ito, 2000)

> "A diamond as uniquely beautiful as the EightStar™ comes to life through a special combination of artistry, technology, and time. The EightStar™ requires commitment to an unprecedented level of quality. EightStar™ cutters work to the most exacting standards. And EightStar™ standards are the highest it the industry…. Look into the EightStar™ pattern and you see the culmination of the quest to create a diamond with perfect light." (EightstarTM webpage, 2012) http://www.eightstar.com/what-is-an-eightstar-diamond.html

We believe such declarations can confuse consumers, reducing their trust and confidence in both diamonds and the industry as a whole. We hold that there should be a verification (validation) procedure for statements like those above.

### *Box A Definitions of "Brilliance"*

**From Tolkowsky's "Diamond Design", 1919:**

The brilliancy or, as it is sometimes termed, the "fire" or the "life" of a gem thus depends entirely upon the play of light in the gem, upon the path of rays of light in the gem. If a gem is so cut or designed that every ray of light passing into it follows the best path possible for producing pleasing effects upon the eye, then the gem is perfectly cut.

**Diamonds, E. Bruton (1978):**

Eric Bruton F.G.A. gives in his book "Diamonds" a definition of brilliance that can be collected from a number of passages of his book: "This quality of returning the maximum amount of light from the stone to the eye – from the surface lustre and from internal reflection – is known as "life". The fire of a gem is the display of spectrum colors (and scintillation) caused by its refracting white light before returned to the eye". "Brilliance has never been exactly defined. As it is used in a general way, it should cover all the visual properties which have been concentrated, in the two last paragraphs, into the terms "life" and "fire". .....The brilliance of a stone depends upon the optimum combination of its life and fire. If the two qualities could be quantified, brilliance would be at maximum when life X fire was at a maximum".

**GIA Diamond Dictionary, 3rd edition:**

Intensity of the internal and external reflections of white light from the crown of a polished diamond or other gemstone. Hardness, refractive index, reflectivity, polish, lustre, and proportions all affect a gemstone's brilliance.

**Diamond Grading ABC by V. Pagel-Theisen, 11th edition:**

External brilliance – lustre, produced by reflection of light on the surface of the facets; Internal brilliance – refraction and total reflection of light on the pavilion facets; Dispersive brilliance – splitting of scattering of light into its spectral colors = the dispersion which evokes the "fire" or "life" in a brilliant; scintillation brilliance – the "sparkle" of the stone when moved, caused by light reflections of the light source.

**Dodson's definition (1978):**

A measure of the light that, entering the crown of the stone, is scattered out of the crown facets.

**"Professional Jeweler" (July 1998) Light Return/Brilliance :**

The amount of light returned to the eye, or brilliance, depends on how well the diamond in question reflects and refracts light. This includes dispersed wavelengths, which are reflected from the internal surfaces of a diamond and returned to the eye.

**GIA (Hemphil et al., 1998):**

White light returned through the crown (excluding glare – light directly reflected from the top surface).

**Garry Holloway:** http://www.diamond-cut.com.au/09_brill.htm

Brilliance is the human perception of diamond brightness. It is the most important feature of a beautiful diamond.

Brilliance is not simply light return; it involves complex issues that include scintillation or contrast with the added variable of human perception. However a diamond with poor light return cannot display optimal beauty.

Fire is the term used to describe flashes of color resulting from spectral separation or dispersion of white light into rainbow flashes.

**Authors from AGS Lab (Sassian et al., 2007):**

**Gem Brilliance** – Gemstone brilliance refers to the ability of a stone to appear illuminated to an observer. For this to occur light must be directed from the virtual facets to the observer's eyes. .... For understanding the illumination appearance of a gem it is useful to think of a gem's facets and their optical projections, the virtual facets, as a collection of tiny prisms that direct light to an observer's eyes. Brilliance [can be defined] as the percentage by area of such tiny prisms that can direct light to the observer's eyes. This definition is simple and does not intend to account for obliquity factors that could be included to account for differences in the relative position of facets or illumination conditions.

**Gem Contrast** – The high angular range ... indicates the zones in a stone's crown that are not illuminated due to the obscuration of the observer's head. This obscuration produces what is known in the trade as gem contrast. In proper amount and distribution, contrast creates structured lighting that enhances brilliance, fire, and scintillation. Contrast can be a detrimental effect if it is significantly localized. Too little contrast results in a stone's appearance lacking variety under broad diffused illumination. Too much contrast results in a stone that lacks brilliance. The combination of positive contrast characteristics and brilliance properties in a gemstone is known as contrast brilliance.

When a gemstone is in movement the contrast pattern changes in form. This effect is called dynamic contrast and adds substantial appeal to the appearance of a stone.

**Gem Fire** – The phenomenon of fire is one of the most appealing effects in transparent gemstones. Under favorable conditions fire makes individual facets appear fully colored with the rainbow hues. Fire inherently occurs due to the light dispersion upon refraction as light enters and exits a stone.

Three factors determine the amount of fire perceived from a facet, namely, the angular dispersion of light upon refraction from the gemstone, the angular subtend of the source, and the angular subtend of the eye's pupil in relation to the facet. To best observe fire it is required to have a localized source of light so that its angular subtend is much smaller than the angular dispersion produced by the gem facet, essentially a point source. As different colored rays arrive to the eye from a facet, some of them enter the eye's pupil and others are blocked producing a colored appearance of the facet. In this process the boundary of the eye's pupil plays a critical role in obstructing portions of the spectrum to achieve the colored facet appearance.

**Gem Scintillation** – In the presence of brilliance and fire the most appealing effect is gem scintillation. Thus there are two major scintillation effects, fire and flash scintillation. To observe them it is required that the stone, the observer, or the illumination conditions be in movement. Typically the observer tilts the stone back and forth to observe scintillation and naturally optimizes for the direction that maximizes scintillation. Without brilliance... there cannot be fire since no light can be brought to the observer's eyes. Without fire there cannot be fire scintillation as defined by the change of fire pattern. Flash scintillation can occur without fire scintillation and it is due to light sources not small enough in angular subtend (point source) to produce fire, or to the inability of a stone to sufficiently disperse light for a given position of the observer. Diffuse white illumination will wash out both scintillation effects. Sources that subtend a small angle will contribute more to produce a flash effect, the rapid turn on and off of the light from a given facet, than sources that subtend larger angles. Thus fire scintillation is more vivid than flash scintillation. The amount of gem scintillation perceived is linked to the brilliance and fire of a stone. However, scintillation strongly depends on the change of illumination conditions. This change is primarily produced on purpose by the movement of the stone as it is admired.

**Pricescope Internet resource** (2010) http://www.pricescope.com/wiki/diamonds/diamond-brilliance-fire-scintillation/

*Brilliance* is an essential attribute of a beautiful diamond and has 2 components: brightness and contrast. Bright diamonds return lots of light from the surroundings back to a 'face up' observer. If light from above leaks out the back of a diamond, naturally it has less brightness. But light that enters and leaves in the face up direction is wasted because your head blocks lights from that direction. Diamonds that are too deep or very shallow do this – they have areas that act like a mirror back to the viewer; they return less light and so they have less brightness.

But to be brilliant, a diamond needs more than just brightness from light return. Consider the contrast of a chessboard, although it has only half the light return of a sheet of white paper, it appears brighter, especially when it is moved because it 'scintillates'.

## *Our reference diamond: standard round brilliant cut*

In his paper "A Study of the Reflection and Refraction of Light in Diamond", Marcel Tolkowsky defines 'Best Proportions of a Diamond': a diamond with a pavilion angle of 40.75°, crown angle of 34.5° and table diameter of 53% (Tolkowsky, 1919). His 2D diamond model did not specify pavilion girdle facets, crown girdle facets and star facets, or girdle thickness. Hence to define our 3D cut model, the definition must be extended to include the outstanding parameters.

We use in our work a cut that we call the Modern Tolkowsky, a modern version of Tolkowsky proportions. This is a diamond model with the parameters shown in Fig. 2.1:

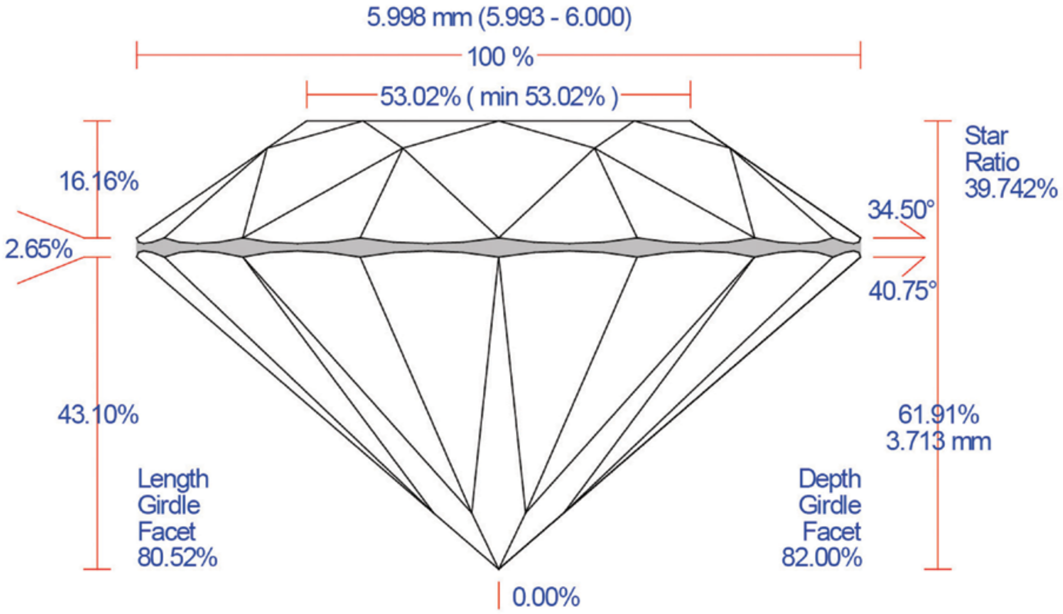



*Figure 2.1 Proportion parameters of the 'Modern Tolkowsky' DiamCalc computer model for which the Performance metrics are given, the base equalling 1.00. The few proportions defined by Tolkowsky are fixed and we defined other parameters not mentioned in his paper. For example the star ratio is such that the table together with eight star facets forms two squares when viewed in the face-up position.*

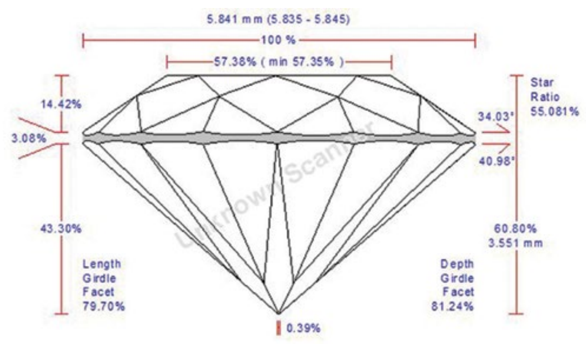
We have used this Modern Tolkowsky diamond model in the DiamCalc software application since about 1997 with its indices and metrics set to equal 1.00. This permits any index of any other diamond (in any cut, parametrically symmetrical or real scanned) to be compared to the same metrics for the Tolkowsky diamond. Given this, it is easy to see whether one or another metric value is higher or lower than that in the reference Modern Tolkowsky diamond. This actual consistent diamond model is used in comparing metrics for all cushion cuts as well as for all other fancy diamond cuts.

We started developing and producing cushion shaped diamonds in 2007 in India, where the cutting facility is located. A reference diamond MSS13, with close proportions to our virtual reference model for visual and video comparison testing, was used. This reference round brilliant cut has a GIA cut grade of 'triple excellent' or Ex Ex Ex. While its proportions are slightly different from those of our Modern Tolkowsky cut, we believe it to be suitable for use as a reference.

Detailed information on this diamond is given in Box B and Fig. 2.2, and its 3D model can be found by following the link http://www.octonus.com/oct/mss/diam13.phtml.

*Box B Geometrical parameters of our reference master diamond MSS 13*

Diamond Master Set Stone: MSS 13: Proportions determined by Helium Polish scanner:




| Parameters | GIA Grading report | OctoNus Helium scan report |
|---|---|---|
| Table | 58 % | 57.38 % |
| Weight | 0.73 ct | 0.7350 ct |
| Diameter | 5.84 - 5.84 mm | 5.841 mm |
| Crown angle | 34 ° | 34.03 ° |
| Pavilion angle | 41 ° | 40.98 ° |
| Star facet | 55 % | 55.08 % |
| Lower facet | 80 % | 79.70 % |
| Culet | None | 0.39 % |
| Girdle | Medium | 3.09 % |

*Figure 2.2 The parameters of MSS 13 from its actual Helium Polish scan. This diamond has been used as an actual standard diamond for comparisons of visual and videos for samples of new cut designs.*

MSS Cutting Rules
Unless otherwise stipulated, all Master Stones Sets (MSS) have:
Face up size equivalent to ca. 5.8mm (5.75 – 5.85)
Hearts and Arrows level symmetry
GIA Ex Polish and symmetry
No painting or digging
G to F Colour
VS2 / SI1 Purity
Non Fluoro
Average Girdle thickness: 3 % at bezel (Medium)
No more than ± 0.3% girdle variation for each diamond
All must achieve GIA EX Cut grade (unless otherwise requested)
e.g. depth percentage must be less than 63%
Star facets: 55 % ± 2%
Lower girdle half Length = 80% (as measured by the GIA) ± 2% (but 78% is better than 82%)

MSS Diamonds Precision
Pavilion ± 0.2° for each diamond. But better precision between diamonds: Crown ± 0.2°, Table ± 0.5%, Girdle ± 0.3%.
Diameter deviation should be within 10 – 20 μm (0.01 – 0.02 mm).
Azimuth (index) variation maximum ± 0.5°. Average less than 0.3°

More MSS set data at: http://www.octonus.com/oct/mss/

## 3. Key concepts used in the study

### *3.1 Brilliance, Scintillation and Fire, as phenomena and our definitions of them*

In earlier works diamond beauty was described as having three phenomena: brilliance, scintillation and fire. Brilliance and fire were considered to be observable in a stationary diamond and only scintillation was considered as a phenomenon for which motion is necessary. When we discussed old definitions with experts, two opinions prevailed. Some believed that brilliance is the same for both static and moving objects, though it's easier to document, study and discuss a static diamond. Others argued that, as the diamond moves and the image changes, all we can see is only scintillation and fire, i.e. a human can only see either brilliance or scintillation at one time – but not both. Most respondents from these two groups say that brilliance is the same as light return from a diamond but all of them had trouble determining or defining what light return actually is. In particular they cannot judge which has higher light return: a good quality mirror or a polished diamond. Our goal in understanding these phenomena was to offer metric equivalents to their human perception.

The main conclusion we found is that to perceive strong brilliance both motion and stereoscopic (stereo) vision are essential. In our opinion, when the gem is static and observed through one eye, brilliance is much weaker in comparison with what we see in motion and/or with both eyes. In this section, we will describe our tests to understand the phenomena of brilliance, scintillation, and fire, and propose our definitions.

### *Brilliance*

To understand what brilliance is, we set up a series of tests to detect the presence or absence of brilliance; the test objects were not necessarily diamond. This work was indispensable for our understanding of the origins of brilliance. Around 2001 it became clear that light intensity is not enough to determine brilliance and that image contrast is also required. Brilliance does not feature when there is either only intensity or only contrast. We also know that there are simultaneously bright and high-contrast complex pattern objects in which brilliance is not observed, for example 'neon' advertising billboards. So even a combination of intensity and contrast may fail to produce brilliance.

In the Stereoscopic tests (described in the Stereo section in detail), we saw small shining squares that superficially resemble what we see on a diamond and invoked similar sensations, although initial intensities of those small squares were not very high, and limited by a fairly low intensity range of the monitor. It is interesting to note that, while earlier monitors had a dynamic range of 1:50 and now they can reach 1:1000, this effect of a shining flashing small square is well visible, yet it appears approximately the same on both earlier and modern monitors.

In impressionism (a painting school), mixed large colour strokes produce a sharp dynamic contrast to increase the dynamic range of subjective intensity of the picture. The impressionistic technique enhances subjective intensity by way of spatial contrast to bring about effects of the types "shining" ray of light, "shining" tree bark, "glittering" silk. These effects cannot be rendered in a conventional technique that does not make use of the features of the human's psychophysiological sight. Nor can these effects be seen on a replica of the painting (they are virtually absent): you must see the original. The origin of shine of a diamond is mainly because each eye simultaneously 'sees' a different intensity at the same spot. The subjectively perceived brightness of a diamond creates the phenomenon of brilliance.

Brilliance is not just about high intensity of a separate element of the image, such as a virtual facet, but something else (Box C introduces virtual facets). We realized that we could perform a series of studies on a computer monitor.

### *Box C Virtual Facets*

A virtual facet of a diamond is created when we look through crown facets and see various pavilion facets and internal reflections. In Fig 3.1 it is apparent that this actual diamond has even more virtual facets than that shown in the wireframe model; these result from the next level of internal reflections, the third, fourth and so on; the virtual diamond facets modelled in the DiamCalc wireframe are only after the second internal light reflection. Our writing published in IDCC1 2004 (see Proceedings, reference 64) lacks detail. The published work by Sassian et al, 2007 while more detailed, is also insufficient in our view. We will discuss virtual facets in much more detail in the second article.

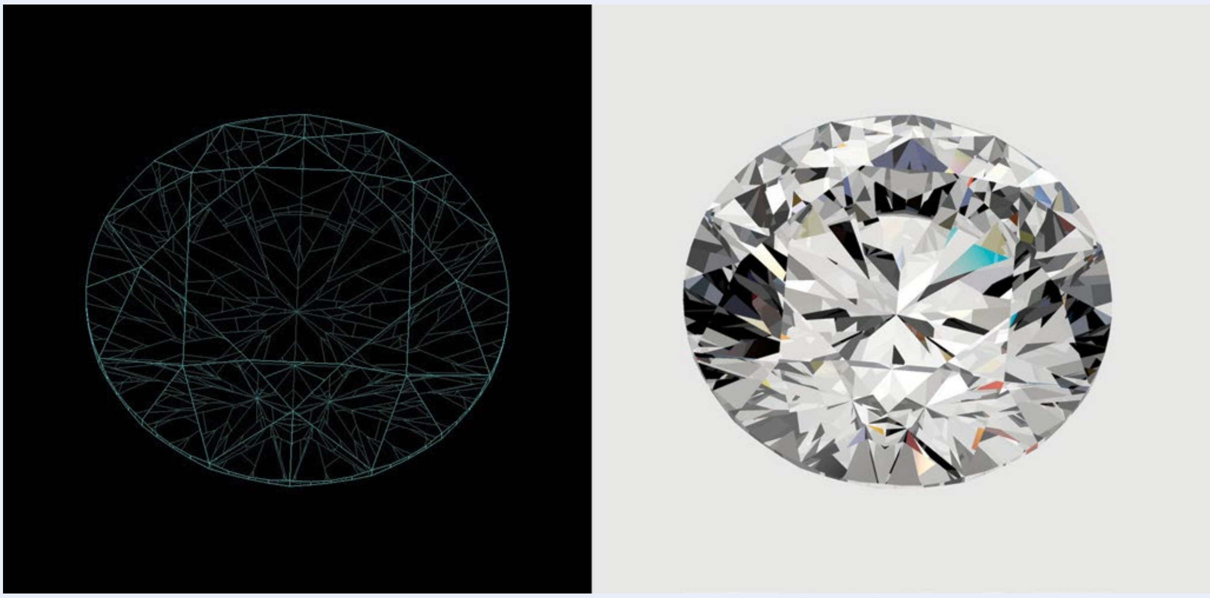


*Figure 3.1 The virtual diamond facets modelled in DiamCalc after the second internal light reflection.*

In the second article we will also introduce a related concept called ETAS (Effective Total Angular Size) which is related to virtual facets and is a methodology of applying metrics to the concept of virtual facets.
OctoNus http://www.gemology.ru/cut/english/conferens-article/7.htm
AGS / Sassian http://www.agslab.com/spie/spie_lo_res.pdf 2007

We know that neither a static image (a photograph) of a diamond on a monitor, nor its printed image has brilliance. Even if, instead of a photograph (photo), we take an image project it to a screen with a very high dynamic range, we will still not see brilliance. So why do all these high intensity and high contrast objects fail to show brilliance? What is absent in them for us not to observe brilliance?

If, instead of a static photo, a movie is watched consisting of a sequence of photos taken while a diamond is rocking; as the switch is made from the separate photo to the movie, we see a new effect - the same virtual facet starts to vary in intensity in response to the gem's motion. Many people report that they see brilliance, although there is still a difference in the perception of 'brilliance' between the movie and the real diamond. If we push the pause button and suspend the movie, the diamond's magic disappears, and we no longer observe the essential element of a diamond's beauty that is brilliance. Thus, no individual photo displays brilliance in itself, and the phenomenon of brilliance only appears when we observe a series of photos at a frequency at which we perceive a continuously changing image.

When watching a movie of a diamond if we still do not get the same perception of a diamond's strong brilliance compared to a real gem, a question arises: what is missing? How can we create a movie that is similar to our psychophysiological perception of a real gem?

The answer appears to be that most people when shown a stereo or 3D movie of a rocking diamond note a high degree of similarity with the perception of brilliance of a real 'live' gem. So maybe it is just about stereo vision? But no, press the pause button and view a still image in stereo, and an essential part of brilliance instantly vanishes.

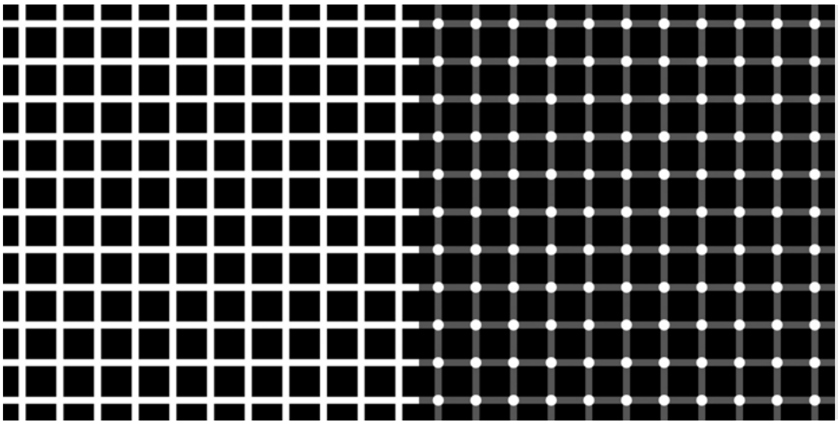


*Figure 3.2 The Hermann-Hering grid illusion and scintillation grid. Note the dark spots are more vivid when viewed with both eyes than with one eye closed. Hermann L (1870). "Eine Erscheinung simultanen Contrastes". Pflügers Archiv für die gesamte Physiologie **3**: 13–15*

There is however still some additional mechanism of brilliance emerging even in a static stereo image when the same spot on a diamond image presents different intensities to each eye; the two images of different intensity arrive at the part of the brain that is responsible for analysing images as we will explain.

When watching a normal mono movie rather than stereo video of a rocked diamond, images of different intensity are continually processed by part of the brain analysing the image of individual segments of the diamond. The same part of the diamond redirects to the eyes different areas of the surrounding space as the diamond rocks. The phenomenon of brilliance emerges because the brain 'observes' different intensities in the same area of space at close moments of time. This effect manifests itself in both the stereo mode of watching a static diamond and the mono mode of watching a moving diamond.

That is why we can see no brilliance on the image of a chessboard, as both eyes see identical intensity for the same board segments, even as the board is rocked.

It may be argued that people observe brilliance in real diamonds even when the gem is static. But each eye is seeing its own picture with different intensities even in a single individual diamond facet, a feature called visual rivalry in the human visual sciences.

We came to the conclusion that in order to observe brilliance, either diamond motion or stereo vision is important.

In our experiments, we could neither accept nor dismiss the possibility of observing brilliance in a static object without the use of stereo vision. In actual diamond observation conditions, there is no way to absolutely fix the diamond relative to the eye. Even if the diamond is static in relation to a light source, the pupil moves continuously as we scan the immediate area, resulting not only in a shift of the diamond image across the retina, but also in small variations in virtual facet intensities. This leads to temporal rivalry in the diamond's image, which is explained later in Section 3.1.

The optical illusions when the observer can see a flicker in static mode are well known, for example the Hermann-Hering Grid illusion (Fig. 3.2 Hermann, 1870). This illusion can be seen in both stereo and mono modes, while in stereo mode the effect is more vivid.

The lateral inhibition and pupil movements are the main reasons for the virtual grey zones flickering in this illusion. The perception of an object with a fine pattern depends to a large extent on the ratio of the pattern size on the eyes retina and the On/Off centre size. This can be as important for the perception of brilliance as it is in the perception of the Hermann-Hering Grid Illusion.

Hence the authors assume that slightly visible brilliance in mid-sized static diamonds (say around 1 carat size) observed through one eye most likely corresponds to the size of virtual facets and is proportional to the amplitude of diamond 'tremor' in relation to the pupil and On/Off centre sizes. When the virtual facets increase to those of, say round brilliant cuts above 20 carat, then the effect of brilliance significantly decreases, and all we see is a high-contrast picture, but not brilliance. For diamonds with very small virtual facets, the authors also did not observe brilliance in a static position.

It should be noted that various devices used nowadays for 'measuring' diamonds' optical performance move either the light source or the diamond. However in the measurements a series of individual static pictures, rather than continuous movies are used. In our opinion, it is impossible to measure brilliance by analysing these pictures separately from each other. Though analysis of individual pictures can yield relevant information, analysis of a continuous movie is required for accurate results. There is something very important for our eyes that is present in a movie and is absent in a series of pictures. The frequency of frame change is important for human perception.

We can see that the essential condition for brilliance to emerge is the presence of a 'visual rivalry' for the human brain originating from contradictory information. That is when the human brain combines reasonably different images seen by two different eyes into one form. This rivalry can have the following origins:

1. **Intensity rivalry:** a certain distribution pattern of areas with various intensities in space, when areas with the same intensity appear as different ones. In this case, the human brain subjectively extends the dynamic range of picture brightness in order to comprehend all the information from a complex picture.
2. **Temporal rivalry:** when intensity varies with a certain frequency within the same area of space.
3. **Binocular rivalry:** when two different eyes see two different intensities (or colours) within one space area and the brain combines them into one unstable image.

To resolve these conflicts, the human brain extends the dynamic range of image intensities to visually make individual diamond virtual facets much brighter than they are in reality. They begin to shine, and we observe brilliance.

To make it possible for us to see brilliance due to the temporal rivalry, fairly large image segments need to change their intensity slowly as the gem moves. If these are small segments or virtual facets with fast changing intensity, we experience scintillation.

Both this motion and stereo vision contribute a lot to the amount of perceived brilliance, which must not be overlooked in designing new cuts to maximize beauty. Moreover, we believe that it is only motion and stereo vision that define the main, and most likely the entire contribution to the perception of brilliance by a consumer. Therefore, for the purpose of developing a first approximation for brilliance metrics, we define brilliance as follows:

**Diamond brilliance is an illusion caused by the fact that the perceived brightness of the object significantly exceeds its actual brightness. This may occur when several**

**parts of the object with different brightness are observed within a single space-time domain. In the case of a diamond, these parts are its virtual facets. Two virtual facets belong to the same space-time domain when an observer cannot separate them due to spatial or temporal limitations of the sense of vision.**

The cause of brilliance is multiple enhancement of the contrast between the dark and light virtual facets, conditioned by the work of the brain. Overlapping of a number of contrast enhancement effects leads to a paradoxical result, impossible to describe, which forces the brain to interpret the phenomenon as brilliance.

While static brightness and contrast are important to take into account in a brilliance metric we believe that without considering both motion and stereo vision, it is not possible to develop a reliable metric to compare different cuts. Our observations lead to the conclusion that motion and stereo are critical inputs into brilliance.

The perception of brilliance remains unaffected by virtual facets reflecting light sources with intensities several times brighter than the average intensity of all sources involved in constructing a diamond image. Virtual facets illuminated by such sources have sharply different characteristics as perceived by the brain that distinguishes them from the phenomenon of brilliance to class them into a phenomenon called scintillation.

Facets displaying colour are also not brilliance and are to be considered as fire.

### *Scintillation*

To further discuss brilliance, scintillation and fire we need to introduce two classifications of light sources based on their influence on diamond performance. The first type (primary) includes relatively bright but at the same time small angular sized light sources, such as the sun, halogen lamps or bright LEDs. Candles may also be considered primary sources: despite not being very bright, their size is small and they are usually present in dark rooms where eyes are adapted to weak overall illumination. In primary lighting, one can see scintillation as bright flashes coming from a diamond (and fire as coloured flashes) but not brilliance. Secondary light sources include relatively dim sources of a relatively large angular size. In the real world, these light sources are often represented by secondary sources like ceilings, walls, furniture, or several fluorescent tubes covered with a single big diffusing cover. In this type of lighting, one can only see brilliance (and fire as coloured facets) and cannot see scintillation (bright flashes). Thus, the difference between brilliance and scintillation is visible under different types of light sources.

As a diamond moves, virtual facets capture secondary light sources for a relatively long time because they have a larger angular size. These virtual facets therefore change in intensity more slowly than those that trap primary light sources with their much smaller angular size. These two light source types produce two sets of virtual facets with very different temporal and intensity characteristics; the brain is unable to consider them a single phenomenon and divides them into brilliance and scintillation. So to define scintillation:

**Scintillation in a diamond is observed as quick bright flashes that appear and disappear when a diamond is moved and illumination originates from bright light sources of small angular size. The same effect is observed when an observer or light source changes position relative to a diamond. A scintillation image changes very quickly with minimal gem rocking because of the small angular size of the light sources. Hence scintillation is not a single pattern but rather a dynamic set of flashes. Fast contrast is an important property of scintillation.** Here, as in the case of brilliance, all coloured parts of flashes should be regarded as fire rather than scintillation.

Brilliance and scintillation cannot be seen on a diamond picture or on a rendered diamond image. One needs a movie to see brilliance and scintillation. A stereo diamond movie is even better as it allows one to observe brilliance and scintillation similar to looking at a real diamond.

Bright scintillation flashes are usually not limited by virtual facet contours and extend past the edges or limits of the facet. At a greater distance from a diamond one can see scintillation flashes that are comparable in size or may even appear significantly bigger than the diamond itself. Such optical phenomena arise from 'bloom' and 'star' effects around scintillation flashes. Their presence originates in visual system aberrations. These effects (see Fig. 3.3) can be seen in a diamond by a human eye or can appear in a diamond photo.

### *Fire*

Fire in a diamond is seen as separate coloured areas and is evaluated and measured on the basis of these separate coloured flashes. Coloured virtual facets (see Box C) in a diamond are characterized by brightness, saturation, size, and lifetime (duration). A combination of brightness and saturation is defined in colour science as 'chroma' in the L*u*v colour space [Hunt, 2004]. Additional attributes of a colour flash are its shape and texture or colour gradient. Like bright scintillation flashes, coloured fire flashes can have 'bloom' and 'star' optical effects (see Fig.3.3).

Fire flashes are different from scintillation flashes because inside a big virtual facet a colour gradient can sometimes be observed. Another attribute of fire flashes is that they can be slower like brilliance flashes and need not be very bright and fast like scintillation flashes. While scintillation flashes result from primary light sources, fire flashes can be created by light sources of both types. Thus fire flashes can be either bright or dull, and their lifetime can be long or short.

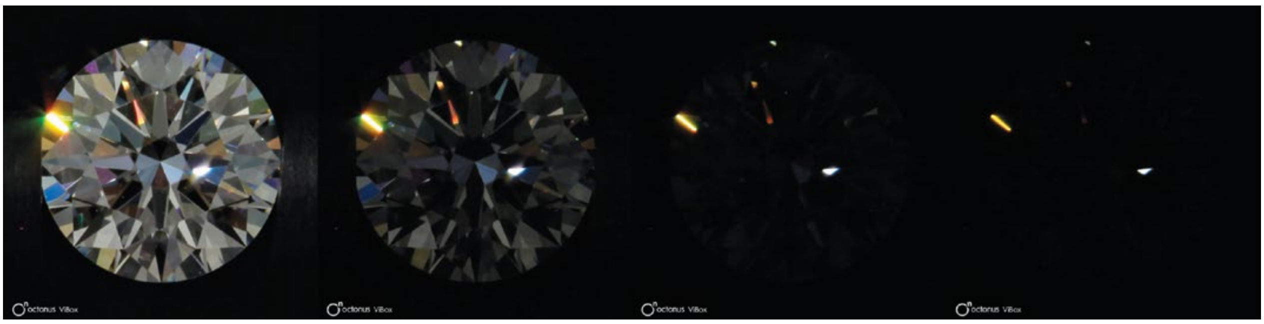


*Figure 3.3 A scintillation flash (white) and a fire flash (coloured) with 'bloom' and 'star' effects. Photos were taken in ViBox with different exposure times and only one white LED as a light source.*

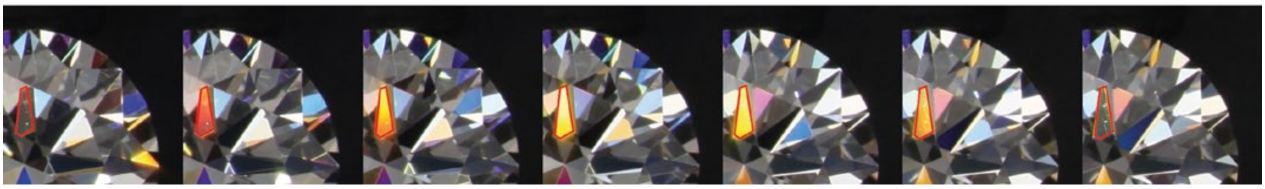


*Figure 3.4 Coloured flashes changing from red to yellow are counted as a single flash.*

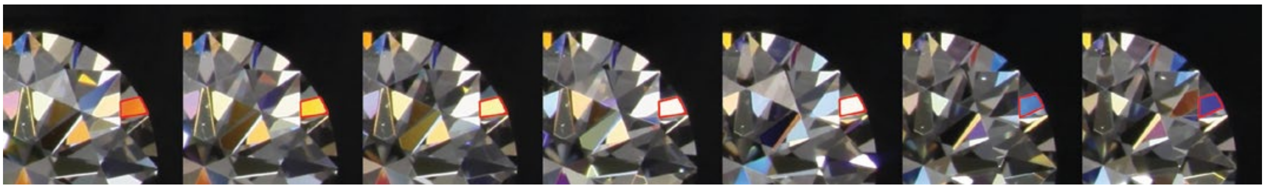


*Figure 3.5 Coloured flashes changing from orange to yellow and white and then to blue and violet are counted as a two flashes on either side of the white flash.*

Unlike brilliance or scintillation, fire can be seen in a static diamond image (photo). It is theoretically possible, and reasonable, to count the coloured flashes in each diamond image while taking into account the colour, shape, size, and brightness of each flash. Then by approximating all the flashes for a set of many diamond images we may determine a 'fire' value for a given diamond. But this method is not correct because a coloured flash in one photo is sometimes also present in subsequent photos and an observer may perceive it as the same flash and not as a new one. For example a flash that is changing from red to yellow is seen as one fire flash (see Fig. 3.4). But a yellow flash in one virtual facet and a red flash in another virtual facet would be perceived as two separate fire flashes, which would be perceived as having more fire even if their total lifetime was less than or equal to a the longer single flash. This is one example to explain why fire cannot be evaluated by separate independent static pictures, if they are not considered as frames of one movie.

When analysing a sequence of diamond images one should take into account how a coloured flash in one image is connected with coloured flashes in the previous and next images. Fire also should be analysed in motion i.e. it is also a dynamic attribute.

For cases when one light source changes colour hue in one virtual facet we use a term 'coloured flash phase'. In the case mentioned above (see again Fig. 3.4), the red phase changes to a yellow phase and would then disappear when the light source is no longer visible through the virtual facets projection in space. In the case where a virtual facet projection crosses a central part of a large light source, we first see one coloured flash, then white light, and then a different coloured flash again, but this next coloured flash is perceived as a new one; a common sequence 'red-yellow-white-blue' is an example (see Fig. 3.5). These flashes are created by one light source but humans perceive the different coloured parts of one flash phase as two separate flashes of colour.

We can see that a diamond with a uniform distribution of coloured flashes looks better than a diamond with the same number of coloured flashes but concentrated only in one part or in several parts. So taking into account all the above we can define fire.

Fire is more evident and attractive for humans when a coloured zone has higher contrast. The reason for this contrast may be in a higher chroma value or in a chroma change in moving diamonds when coloured flashes suddenly appear and disappear. Local contrast of a separate flash depends on its surrounding, i.e. surrounding virtual facets colour and brightness. In this respect, a coloured flash appears with more contrast against a black background than the same flash with surrounding virtual facets against a white background. In other words, brightness and fire can compete with each other in one diamond and there is no diamond cut which is the best both in terms of brightness and fire at the same time.

**Fire is the simultaneous (local) contrast of colour that is observed in a diamond. The contrast of this coloured image depends on surrounding areas and on the duration of a coloured flash. If the coloured flash is too fast the eye is not able to comprehend its colour and such a flash is perceived as scintillation. If the coloured flash lasts too long its total contrast is less than the sum of the contrast of two separate shorter coloured flashes of half the lifetime of the initial flash. For a flash to be perceived as coloured it should not be neither too fast, too small or too bright; when combined these factors make a coloured flash appear to a human as scintillation and not a fire flash.**

## *Importance of contrast in a diamond*

When we consider all three definitions for brilliance, scintillation and fire, we note that they include contrasts of three different types: in brightness, in colour, or in time, and all these parameters are essential for brilliance, fire, and scintillation. In other words diamond's beauty for humans is highly related to changes in a diamond image or movie. These changes are projected to the eye retina and further are perceived by the human brain as an attractive image or movie. A polished diamond can be considered as a unique optical object because it creates all three types of contrast for a human brain at the same time.

**Brilliance** is slow (but not low) contrast from point to point, from time to time. Because the changes are slow, the human brain interprets it as a united image with a wider range of dynamic brightness. The contrast of a static image is that with zero speed.

**Fire** is colour contrast. Coloured fire contrast can be slow or fast. Slow contrast fire is usually created by the same secondary light sources that are responsible for brilliance. Fast contrast can be created by primary light sources that are responsible for scintillation and also, sometimes, by secondary light sources.

**Scintillation** is fast contrast. The image changes dramatically in a very short time producing scintillation. At one moment of time, flashes appear at some places and in the next moment other flashes appear elsewhere. This change is so fast that the human brain cannot see it as one image; the process is stochastic.

Different diamonds can have different combinations of brilliance, scintillation, and fire. These combinations of attributes described here give different performance (or 'life' as it called in some literature) types.

The definitions given in this section serve as a basis for the development of High Light Performance cuts. They enable the creation of working software metrics and the development of reliable visual assessment methodologies and tools. We understand that these definitions are too complex and probably will not be effective for communication with end consumers. We believe that it is important to develop other terms and definitions for more effective buyer/seller communications.

*Figure 3.6 A Cyclops mono image of a Round Diamond above.*

*Figure 3.7 Left and Right eye ViBox stereo image of the same Round Diamond to demonstrate how far images for the left and right eyes differ from what a Cyclops observer sees. How the final image is formed in the brain is based on two images. In order to see what result the brain will see, these photo pairs may be viewed using the stereo glasses included in this journal, or for better results, in special stereo viewing software.*

## 3.2 Human Stereo Vision Properties

In this section we discuss the basis of stereo vision as one of the main factors of our work and prove the importance of taking stereo effects into consideration for cut development and assessment. The ways of using stereo in metrics and cut analysis (assessment) are discussed in other sections below.

It is important to understand how the Stereo effect manifests itself when viewing a diamond through two eyes, and how a single image is formed out of two images in a human brain. When a human views a diamond through two eyes, each eye sees the diamond from a certain angle, while the diamond image consists of a set of virtual facets. Sometimes both eyes see the same virtual facet nearly the same way (in terms of shape, colour, brightness), and in some cases the information received by one eye differs from that of the other. For this reason a mono image of a diamond, for example in a photo, or on a computer display, differs from the image that is formed in the brain.

There are certain problems with illustrating stereo effect on paper because images are 2-dimensional while stereo effect includes a 3-dimensional image. In practice there are different stereo visualisation technologies used for viewing stereo images, for example on a stereo monitor or a stereo TV. These technologies are implemented in such a way that the left eye perceives the image for the left eye, and the right eye perceives the image for the right eye. This way we can understand the result a human sees. In this article we show two images next to each other - for the left and right eyes - and explain what a human will see in stereo mode. Diamond photos are usually larger than real gem size, which allow people to see and analyse the details that are harder to distinguish when viewing real gems. Fig.3.6 shows a cyclops mono image of a round brilliant cut.

In Fig. 3.7 we show how this diamond looks for the left and right eyes in the same illumination conditions. In fact the resulting image for the human brain will differ from these images as well.

Fig. 3.7 shows that the left eye sees, in the gem's table, three elongated black areas for which the main pavilion facets are responsible, and the right eye sees three different similar areas. The areas that appear dark to one eye, are light to the other, and vice versa. In a photo these areas emerge due to the camera lens being reflected in the diamond, and in real conditions this happens due to reflection of the observer's head. In real conditions the brain sees neither dark nor light areas but sees brilliance in their place. What brilliance is and how it emerges is easier to understand using examples of simpler objects than diamond facets. To this end we describe tests with squares in black, white and grey backgrounds below (Subsection: tests with squares).

Based on analysis of a large number of gems in mono and stereo modes, we can point out that a lot of Excellent and Very Good diamonds differ from each other less than a single gem's image in mono mode differs from the same gem's image in stereo mode. That is why we believe that it is incorrect to assess the performance using only mono images. This is not just a problem of photo images or computer models used for assessing performance. Specialists also assess real gems through a magnifying glass with one eye, thus working in conditions very close to a Cyclops view, while consumers assess gems with both eyes, so experts and consumers often view gems in different conditions and see them differently. We believe that stereo is very important, and below we will show how many different phenomena occur in stereo observation and how stereo creates the unique 'Life' of a diamond.

### Tests with squares

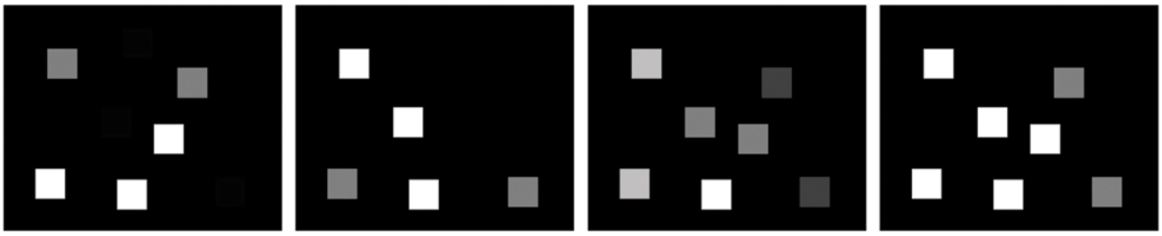
In order to find out how a human brain transforms two images into one, we started with a study of an object simpler than a diamond. In real life two eyes usually see objects of the same brightness. In the case of a chessboard both eyes see the same square, which is not the case for a diamond. This is the main difference between a diamond and most objects that we see in the world around us. That is why we have chosen a simplified object that each eye sees differently. It is a square (a white, a grey or a black one) that may be positioned in different backgrounds: a white, a grey or a black one. We create different brightness of the squares for each eye while the brightness of the background does not change (see Fig 3.8 and its caption).

There is a mechanism of brilliance appearing in a stereo image when the same area of a diamond has a different brightness for each eye, and two images with different brightness enter the brain region that is responsible for analysing the image of the same area of the square, or a diamond.

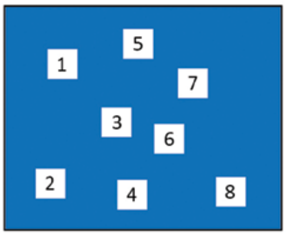
If the left eye sees a white square in a grey background and the right eye sees a black square in the same grey background, then these two images can be combined using stereo glasses, so that they are in the same place for each eye. A person will then see a square blinking with a frequency of about 2 hertz, the image of which will have metallic lustre absent in both the white and black squares, i.e. a totally new phenomenon. The amount of this lustre changes over time, and from time to time the square looks purely black or purely white for short periods, and between these periods its brightness is hard for the eyes to determine and assess. If we simultaneously display stereo and mono images in this test the observer will assess the subjective brightness of the square in the stereo image to be higher than in the mono image where a white square is placed into a black background due to the perception of lustre.

## Black background

Left eye sees | Right eye sees | Average brightness | Brain perceives

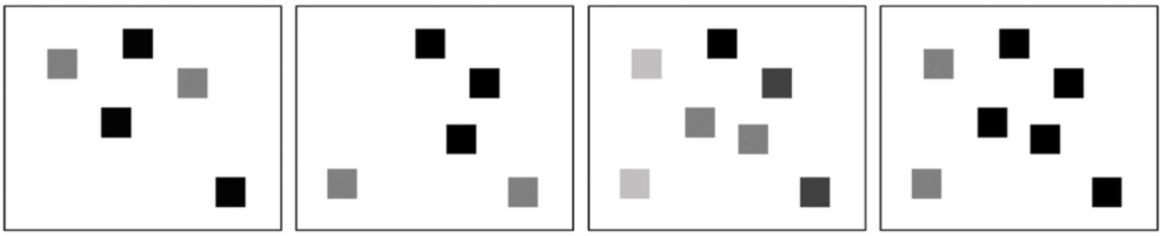


| N | Left eye | Right eye | Average brightness | Brain perceives |
|---|---|---|---|---|
| 1 | grey | white | light grey | white |
| 2 | white | grey | light grey | white |
| **3** | **black** | **white** | **grey** | **white** |
| 4 | white | white | white | white |
| 5 | black | black | black | black |
| **6** | **white** | **black** | **grey** | **white** |
| 7 | grey | black | dark grey | grey |
| 8 | black | grey | dark grey | grey |

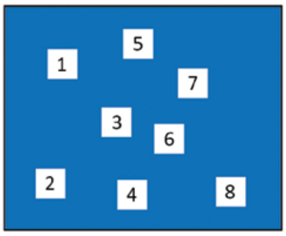



## White background

Left eye sees | Right eye sees | Average brightness | Brain perceives

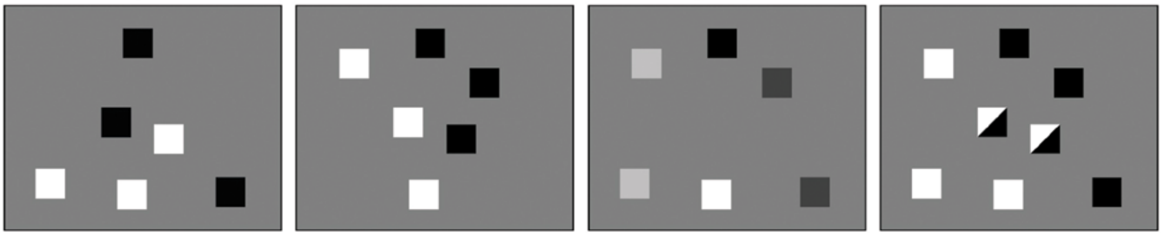


| N | Left eye | Right eye | Average brightness | Brain perceives |
|---|---|---|---|---|
| 1 | grey | white | light grey | grey |
| 2 | white | grey | light grey | grey |
| **3** | **black** | **white** | **grey** | **black** |
| 4 | white | white | white | white |
| 5 | black | black | black | black |
| **6** | **white** | **black** | **grey** | **black** |
| 7 | grey | black | dark grey | black |
| 8 | black | grey | dark grey | black |




## Grey background

Left eye sees | Right eye sees | Average brightness | Brain perceives



| N | Left eye | Right eye | Average brightness | Brain perceives |
|---|---|---|---|---|
| 1 | grey | white | light grey | white |
| 2 | white | grey | light grey | white |
| **3** | **black** | **white** | **grey** | **sparkling and blinking** |
| 4 | white | white | white | white |
| 5 | black | black | black | black |
| **6** | **white** | **black** | **grey** | **sparkling and blinking** |
| 7 | grey | black | dark grey | black |
| 8 | black | grey | dark grey | black |

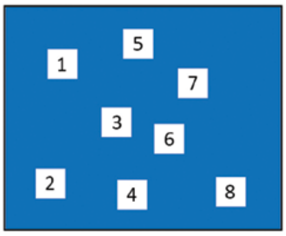



*Figure 3.8 Stereo vision tests with different background colours. The top image shows squares on a black background, and the middle image shows squares on a white background. Each of the images shows what the left eye sees, what the right eye sees and the result that the brain 'sees'. The bottom image displays the same squares but on a grey background. On the grey background the brain sees brilliance when one eye sees a white square and the other eye sees a black square (shown as a black & white square in the Brain perception column). These features can be seen with the stereo viewer supplied with this journal. All these tests with squares are available in the file depository.*

A similar phenomena creates brilliance, which is especially notable in round cuts as seen in the main pavilion facets within the table in diamonds with good proportions such as a modern Tolkowsky cut (for example, see Fig. 3.7 in stereo mode).

An important comment: the squares in these tests are models - they do not fully correspond to the virtual facets of real diamonds. Real diamond facets can have a much wider range of brightness (the brightness of squares is limited by the display capability). While viewing the display in stereo mode, we see a lustre that is brighter than the white colour of the square. But when observing a real diamond in real conditions, the subjective brightness of its facet may be intensified much more because the light ray in the diamond begins from a primary light source that may have significantly more light power than the display. What we mean here is not the external lustre of light reflected from the diamond's surface, which the brain often 'filters' in static positions of the diamond, but inner reflections creating bright flashes and brilliance. External lustre will be analysed below.

The actual facets of a diamond also have a much smaller angular size than the squares do because diamonds are generally small objects. However this model test is valuable because the squares allow us to easily see the uncommon effects of stereo vision, due to their simplicity, compared to real facets.

In this article we describe and discuss only one test with squares, while some readers may be interested in our other tests with figures of different shape, colour, brightness and activity over time, which can be found in the annex base in the depository.

We create these tests with squares so that we can control the behaviour of a certain effect in each test. In a real diamond multiple effects are mixed up and it is hard to distinguish their individual influence on the result. This way we try to classify these phenomena. These tests show how complex the processes in a human brain are that lead to generation of an image of a diamond based on the information received by two optic canals.

### *Information maximisation principle*

Besides the situation when one facet is white for one eye and another facet is dark for the other eye, there are many other cases when the brain receives unequal and often contradictory information from each eye. In these cases it is not obvious how the brain forms the final image. One of these cases is when only one eye sees glare across an entire facet caused by external reflection.

Let us consider an example of a diamond photographed as a stereo pair in ViBox using a stereo adapter. In Fig. 3.9 left, the table of a round diamond does not contain an external fleck, so the left eye sees all virtual facets under the table. At the same time the right eye sees a fleck in the diamond's table (area 'A'). The question is: if the right eye sees a glare and the left eye sees several virtual facets in the same place, what will the brain see?

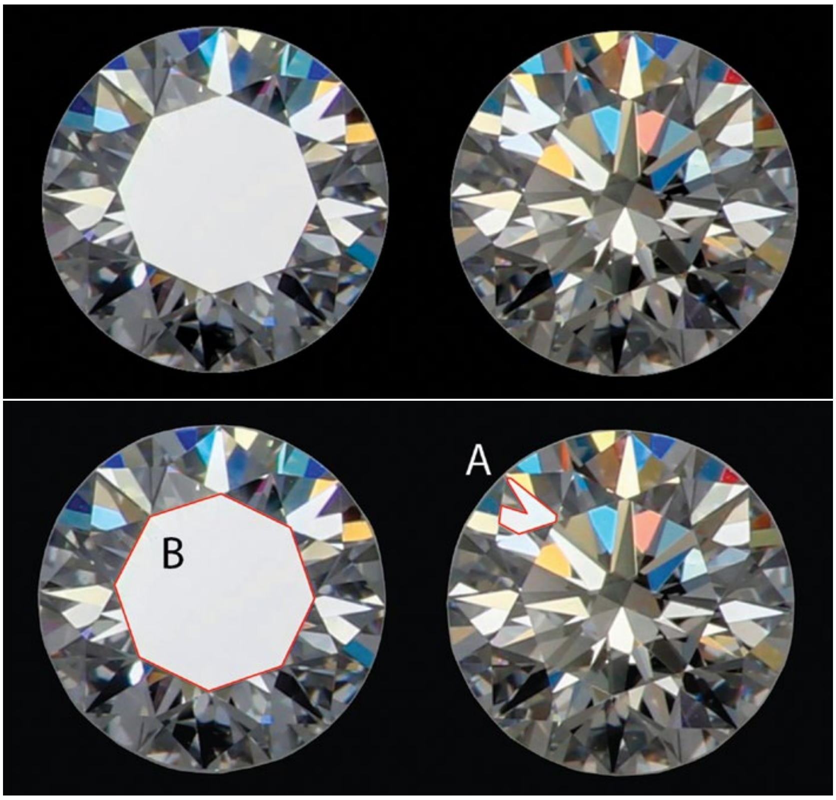



*Figure 3.9 Two diamonds photographed in stereo with left and right eye views as they would be observed in real life. When observing the stereo pair with the stereo viewer the important details from each image are combined by the brain.*

It is paradoxical, but when the diamond is stationary in a stereo image a human does not see the external glare on a table, but sees the facets under it. This means that in this part of the image the picture in the brain is created based on the information that the left eye receives. If we analyse the area marked with 'B' in Fig. 3.9, in stereo observation a human will see the more informative area, which the left eye sees. That is, in this example part of the image in the brain is inherited from the left eye image, and the other part – from the right eye image. It would be incorrect to say that one eye always dominates.

Based on viewing diamond stereo movies and special model stereo principle tests, we have arrived at the conclusion that vision works in accordance with a so called information maximisation principle: that is the brain chooses images from each eye that contain the maximum information about the object and generates the final image based on these. In the case of a static image the information maximisation principle works in such a way that the brain does not see the large glare on the table but sees a complex pattern of virtual facets. In motion the glare's informational weight increases, especially at the moment when it suddenly appears in sight. That is why in case of a moving gem the brain will see the glare on the table instead of small virtual facets and will continue seeing it for some time. In the case of long observation of the glare, the brain may 'switch' back to small virtual facets.

Brilliance that emerges for the same facet that appears white and black for alternate eyes at the same time also fits this information maximisation principle. The reason for this is that the brain tries to keep data from equivalently informative parts of the image, but as this information is contradictory the brain transforms it with the lustre illusion creating the brilliance effect as in the test with squares above in Fig 3.8.

In Section 3.1, we introduced a definition for flash duration or lifetime. In studying stereo vision we see dynamic changes during flash durations as we observe them with two eyes. There is an optimal flash duration (see Human Vision section). When rotating the gem, the flash in area A (Fig. 3.9) may last so long that it will disappear from the brain at some moment, although one of the eyes continues seeing it. While area B is a glare in the external surface, area A is a flash (a set of flashes) for which the virtual facets are responsible (i.e. it is not an external reflection). This means that the information maximisation principle may

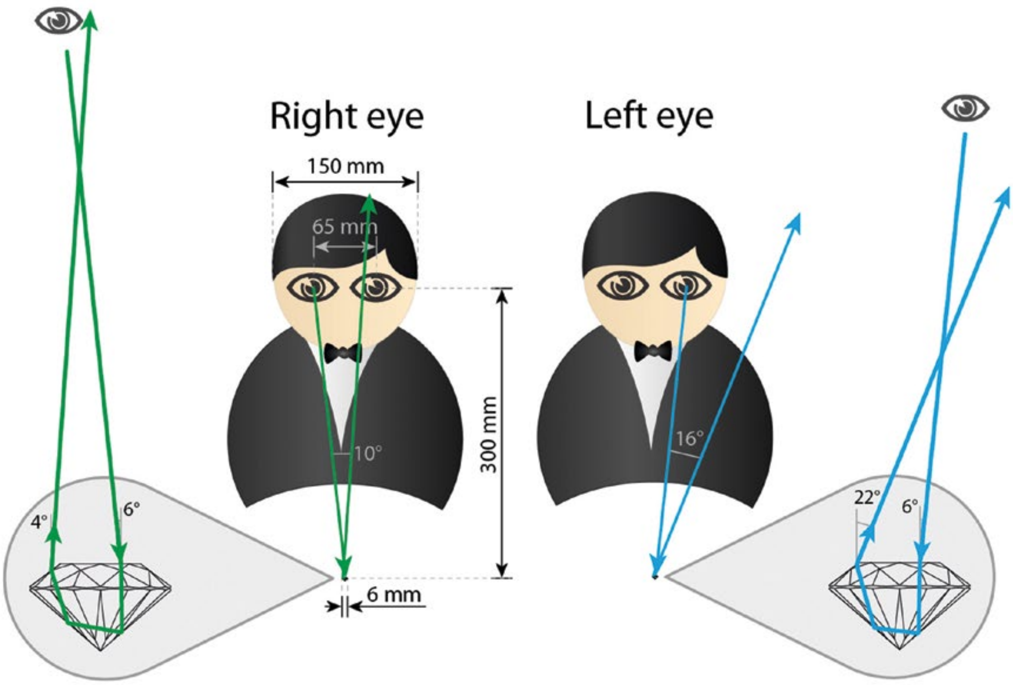



*Figure 3.10 Two traces of light rays drawn to suggest light 'coming out' from different eyes and entering the same point on a diamond table. Modern Tolkowsky proportions are used for ray tracing (see Fig. 2.1).*

limit the time of observing a flash. A human stops seeing the flash because it disappears as neither of the eyes sees it, and also in the case that one eye continues seeing it but due to its longer duration it loses to a more detailed image that the other eye sees here in terms of the information maximum. For the other (right) eye the information in this area constantly changes as the gem moves, and the result thus depends on both stereo and on dynamics.

Included on the web-site listed in the appendix to this article in the test with squares there are tests where the squares are split in segments with differing detail. These modelled objects allow readers to see a variety of effects emerging in a brain while observing contradicting information by two optical channels. These tests are provided for anyone who has a stereo monitor wishing to ascertain these results.

## *Features of a binocular observer*

For the development of new cuts with high optical performance preferred by consumers, further understanding of the mechanisms which force the stereo observer to have contradictory information in both optical channels is important.

The reason for the unique feature of diamonds (the same area giving different brightness for the left and right eyes) is that the left and right eyes usually see images of different light sources (or their parts) from the same area of the diamond. This is because of the distance between the respective eyes, and this phenomenon becomes clear if we draw (trace) rays from the left and right eyes that exit the same point in the diamond, but at different angles (Fig. 3.10). Furthermore the rays to the left and right eyes that enter the same point in the diamond can exit the diamond in widely different points and directions after multiple inner reflections.

While observing a diamond it is important that its appearance is influenced by obscuration of the space occupied by the observer's head and body as noted by many previous researchers. Yet most prior studies were based on a cyclopean monoscopic observer, ignoring the non-symmetric obscuration caused by different eye-head edge distance. But at the same time these studies did not expand the influence of non-symmetry of such obscuration, caused by different eye-head edge distances in a plane set by observation vectors of some point on a diamond, on the Appearance and Brilliancy in particular. Such an observer is different from a simpler model with one eye in the centre of a head further called Cyclops.

Harding (1975) discussed that a real observer has two eyes and that the minimal obscuration angle is less than for a cyclops viewer with the same head size. The non-symmetrical obscuration of light by an average observer's head size in relation to a diamond from a viewing distance of 30 cm is approximately 8 degrees for each eye. Harding mentions 10 degrees in one direction, and 20 degrees in another (see Fig. 3.11) which has a significantly different effect on the appearance and brilliancy of a diamond when compared to a cyclops modelled obscuration angle of 14 degrees in each direction (see Fig. 3.12).

The first is stereo contrast. There is very high probability that the same facet will be observed as a black one by one eye and as a white one by another (see Fig. 3.13). This creates stereo contrast which enhances brilliance (see the Brilliance section). As explained above, this type of optical illusion subjectively increases the brightness of the corresponding areas in the diamond and consequently the whole diamond.

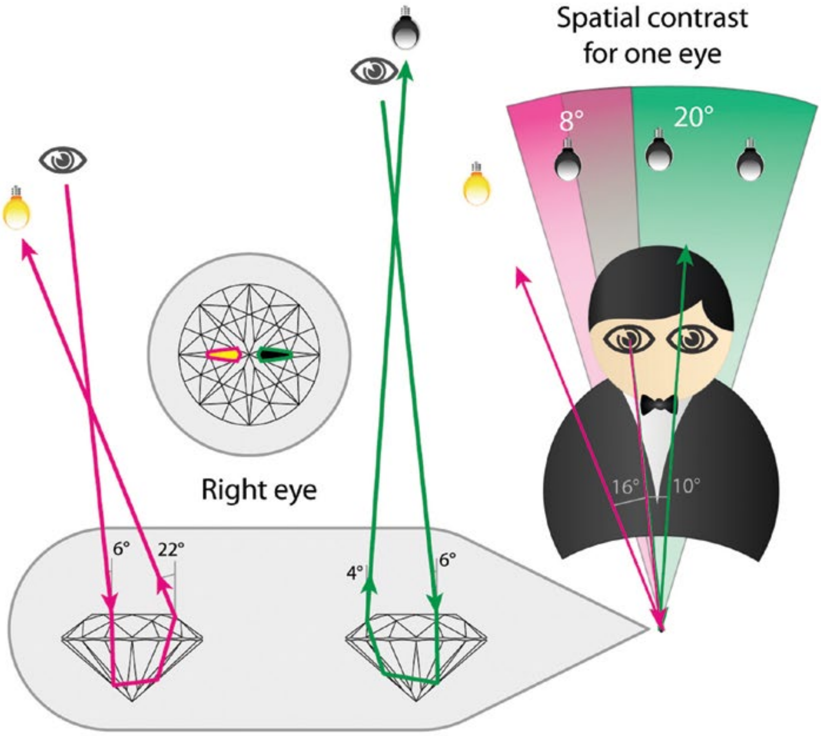



*Figure 3.11 Spatial contrast. Spatial contrast emerging due to non-symmetrical light source obscuration by a head (for crossing ray). Opposite pavilion facets under a table are observed as light and dark by the same eye.*

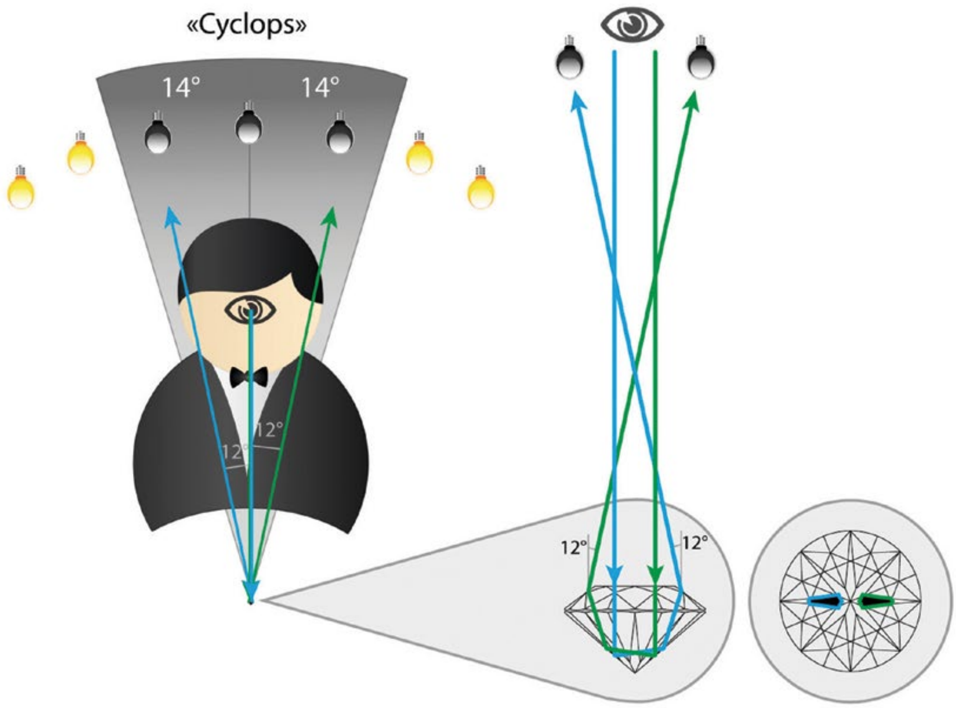



*Figure 3.12 Scheme of diamond observation for a cyclops observer. Both facets would appear dark.*
*There are two important consequences in the case of a real observation of a round Tolkowsky diamond in comparison with that of a Cyclops model.*

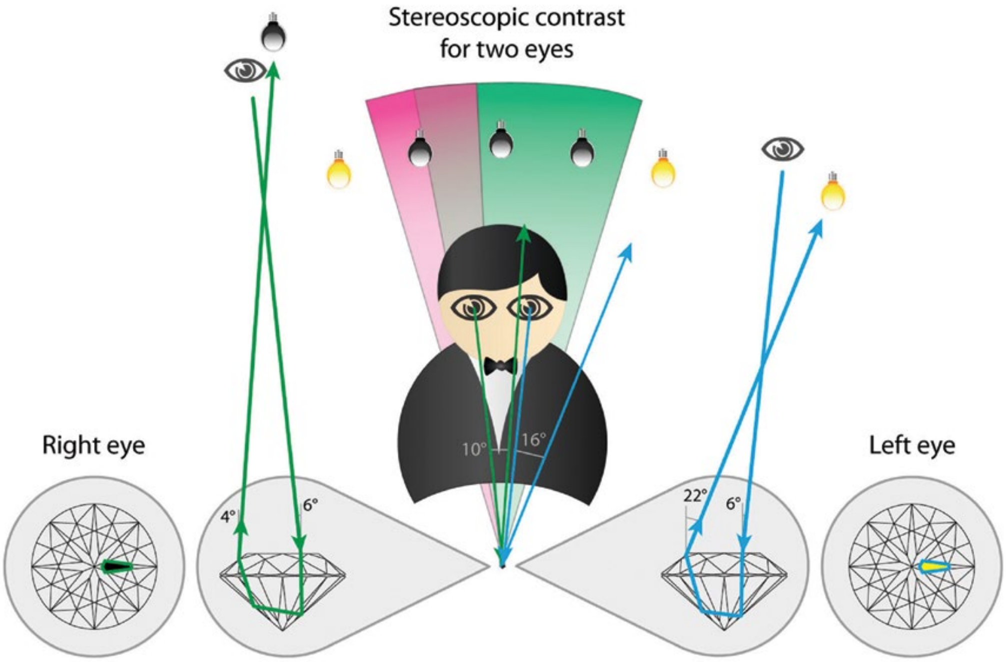



*Figure 3.13 Shows an example of stereo contrast emerging when simultaneously observing one facet with two eyes. For this observation the facet is light for one eye and dark for another creating the perception of stereo contrast.*

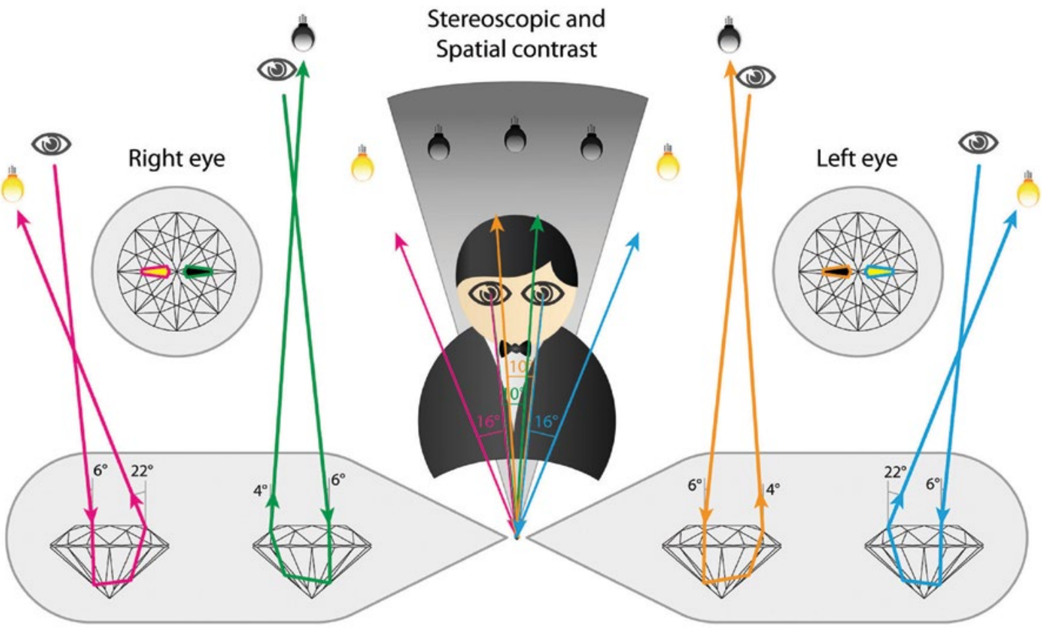



*Figure 3.14 Spatial and stereo contrast for a Tolkowsky diamond.*

The second consequence is an increase of spatial contrast. That is if one pavilion facet is light for right eye and dark for the left (see Fig. 3.14), then the opposite pavilion facet is, light for the left eye and dark for the right eye. So there is high probability for a real observer to experience both types of contrast at the same time: stereo and spatial. A cyclopean observer will see neither stereo nor spatial contrast as both facets are either simply light or dark.

The Fig 3.14 illustrates that the pavilion facets of Tolkowsky diamond cut have both spatial and stereo contrast at the same time.

The importance of these types of contrast for diamond perception can be illustrated by comparison with a round brilliant cut with a 25 degree slope of crown facets and 39 degree slope of pavilion facets (Fig. 3.15). Although this cut has very low leakage and high light return, the life of a diamond with these proportions is at a disadvantage in comparison with the Tolkowsky round cut with 34.5 degree slope of crown facets and 40.75 degree slope of pavilion facets (in the examples above) because these facet angles lead to reduction in ray obscuration by the observer's head and, consequently, both spatial and stereo contrast is dramatically reduced.

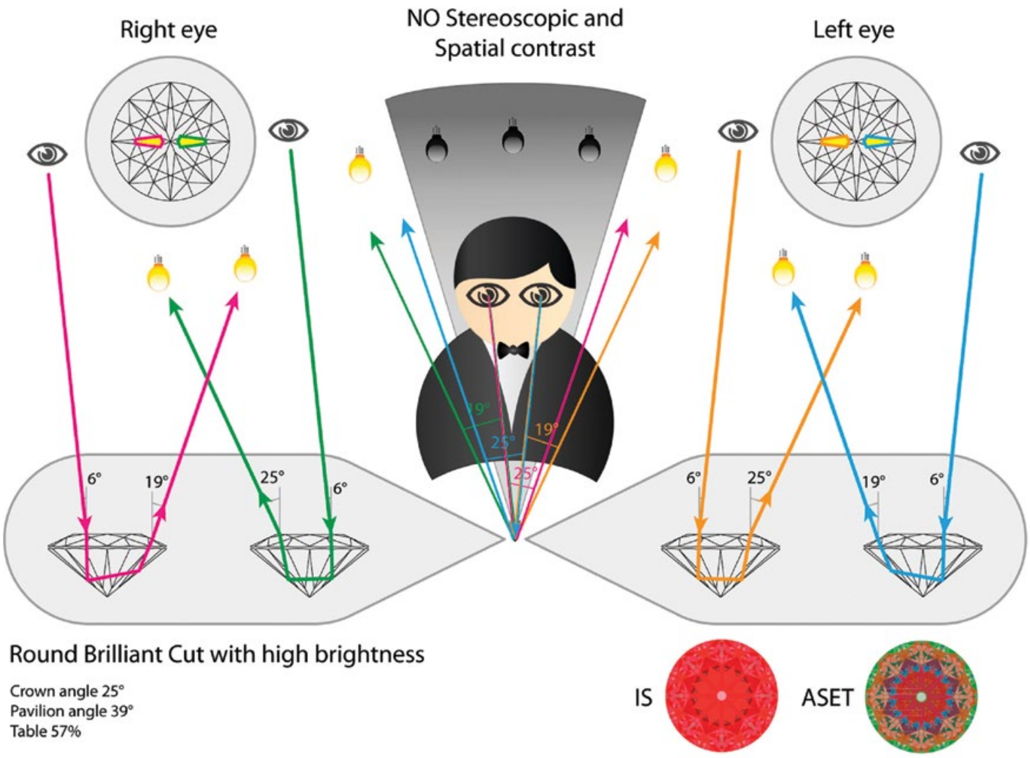



*Figure 3.15 Round diamond with 25 degree slope of crown facets and 39 degree slope of pavilion facets with no leakage and with high light return, but with no such spatial and stereo contrast as with a Tolkowsky diamond cut, because the facet angle variance results in a change in obscuration by an observer's head.*

A practical example of the difference in cyclops and stereo observer's views can be illustrated by the ASET™ device which predicts obscuration which will be represented as blue. However the non-symmetrical eye position of a real observer reduces the obscuration angle by a factor of about two times, i.e. total head obscuration is around 28 degrees (a cyclops view has about 14 degrees from each side of the imaginary head) whereas a human has around 8 degrees obscuration from one eye and 20 degrees from the other. Thus many facets in a diamond considered unable to return light from surrounding sources by the ASET™ device may actually capture light from sources and return it to one or the other observer's eye.

Another example illustrating the importance of human stereo vision is areas that the eye sees as dark because of light leakage through the diamond pavilion. Tools for viewing leakage using structured illumination, such as the Firescope™, Ideal-Scope™ and ASET™ assess leakage from a single monoscopic view in the face-up position. However often when observing the same area through two eyes, one eye may see the dark leakage zone, but the other eye may see a bright area and the brain will perceive this area as bright.

The human stereo phenomenon is also important for the perception of fire and its evaluation. We noticed that for some cuts in stereo mode humans observe approximately two times as many coloured flashes than when observing with the left or right eye separately. While in other cuts a human in stereo mode observes a similar amount, sometimes a little more and sometimes a few less coloured flashes than when observing the diamond with each eye separately. This observation brings our attention to an observation regarding a single light flash seen simultaneously by both eyes. In the Brilliance, Scintillation and Fire section (3.1) we discuss the meaning of the term "Flash lifetime" from an observer's point of view. For analysis of this human vision phenomenon it is necessary to discuss the angular extent of a flash that we determine as the maximum angle of diamond rotation for the flash to remain visible, or the angular extent of observation rotation if the viewing direction is changing. To observe one flash with both eyes then the angular extent of this flash must be relatively large. Coloured flashes in round cuts, with long narrow facets, often have a relatively long angular extent and may be seen simultaneously by both your eyes. Some other cuts have a short angular extent and so may only rarely see the same coloured flash with both eyes simultaneously. This idea is the subject of further research by the authors and will be considered in detail in a future paper to be published shortly.

### *Methods to obtain stereo image pairs and stereo movies of diamonds*

The Vi-Box device for diamond photography (see Section 4) was created to obtain stereo image pairs and stereo movies of diamonds in the same repeatable conditions. A special image splitter (stereo adapter) mounted on a macro lens of a camera enables the capture of two sets of images as would be seen by an observer with left and right eyes (see Fig. 4.1). Software creates stereo movies that can be viewed with various modern stereo visualization methods including stereo glasses and 3D screens. Stereo diamond movies are more realistic and close to actual human observation of diamonds.

In conclusion, it is clear that the perception of brilliance depends greatly on properties of human stereo vision. Without accounting for stereo vision it is impossible to create an accurate optical performance evaluation system and metrics.

## 3.3 Human visual perception features and their influence on the optical performance of diamonds

Human vision is a complex mechanism of visual data extraction and interpretation. A variety of factors affect the perception process making it complicated for modelling. However, a study of human visual factors is essential both to understand why diamonds look so attractive, and to simulate, numerically appraise, and mathematically prove why one diamond is more attractive than another. We will show that in order to correctly model human perception of a diamond, it is necessary to take into account changes taking place during a diamond's natural rocking, and to account for binocular vision, more so than the appraisal of static images. The facts and data in this section prove the occurrence of brilliance as described and defined in Section 3.1, on the basis of the current knowledge and laws of visual perception.

The main parts of the human vision system are the eyes, the visual nerves, the lateral geniculate nucleus (LGN; the primary relay centre for visual information received from the retina of the eye), and the visual cortex of the brain (Schmidt and Thews, 1989). In all these structures, complex visual information processing takes place. As a result of multi-stage signal processing, a wide range of interesting effects and phenomena occur.

Low-level effects are associated with processes taking place in the eye's retina. They are quite well studied and described in the literature; a lot of experimental data has been collected. A brief description of the most important aspects of the structure and the functionality of the retina can be found in Box C. The low-level effects include spatial and dynamic contrast, brightness perception nonlinearity, and light adaptation.

We call the high-level effects those that occur at the level of the LGN, the visual cortex, and solving problems associated with stereo vision, attention, object detection and analysis, and phenomena evaluation (both qualitative and quantitative). These high level effects have had much less study and are only understood in terms of hypotheses about their implementation in the visual system.

We describe and explain in this section, the low-level effects, and briefly consider the key high-level mechanisms that are important for evaluation of the perceived properties of diamond.

### *Physiology of Vision and Spatial Effects*

#### Lateral Inhibition, Global and Local Contrast

The human vision system evolved to extract the greatest amount of information from an image including all levels of visual structure. Most of the information in an image is contained within sharp edges and details while areas that are visually continuous contain much less information. Thus the perception of the principle of contrast is fundamental to the primary function of human visual systems. In the retina, this principle occurs as the lateral inhibition mechanism that is explained in technical detail in Box C.

In the example of the "Mach bands" illusion (Ratliff, 1965, Fig. 5) we demonstrate the lateral inhibition mechanism's effect on human visual perception. Fig. 3.16 (a) shows seven vertical bands of different shades, but each is of uniform brightness. To an observer there are illusory brightness stripes near the junctions or sides of each band: lighter appearance to the right of the junctions and a darker appearance on the left sides.

Fig. 3.16 (b) illustrates the responses of ganglion cells for different zones of the Mach band pattern. An on-type ganglion cell with the receptive fields centre tangent to the edge from the left (B) receives a smaller inhibition signal and appears lighter than the central zone within the brighter band (A). Conversely the edge in the darker band (C) receives a larger inhibition signal and appears darker than the central area (D) because its left surrounding perceives more light from the adjoining lighter band. For full understanding of these effects we direct the reader to Box D. In short, the ganglion cells in the retina of the eyes receive a positive signal in the centre, as represented by the '+' sign in the inner circle in Fig. 3.16 (b), and a negative signal in the surrounding part of the cell, as shown with four '-' signs in the outer circle. The positive signal is significantly larger, so in the case of B there is a reduction in the negative signal because the ganglion cell is overlapping into the darker band:

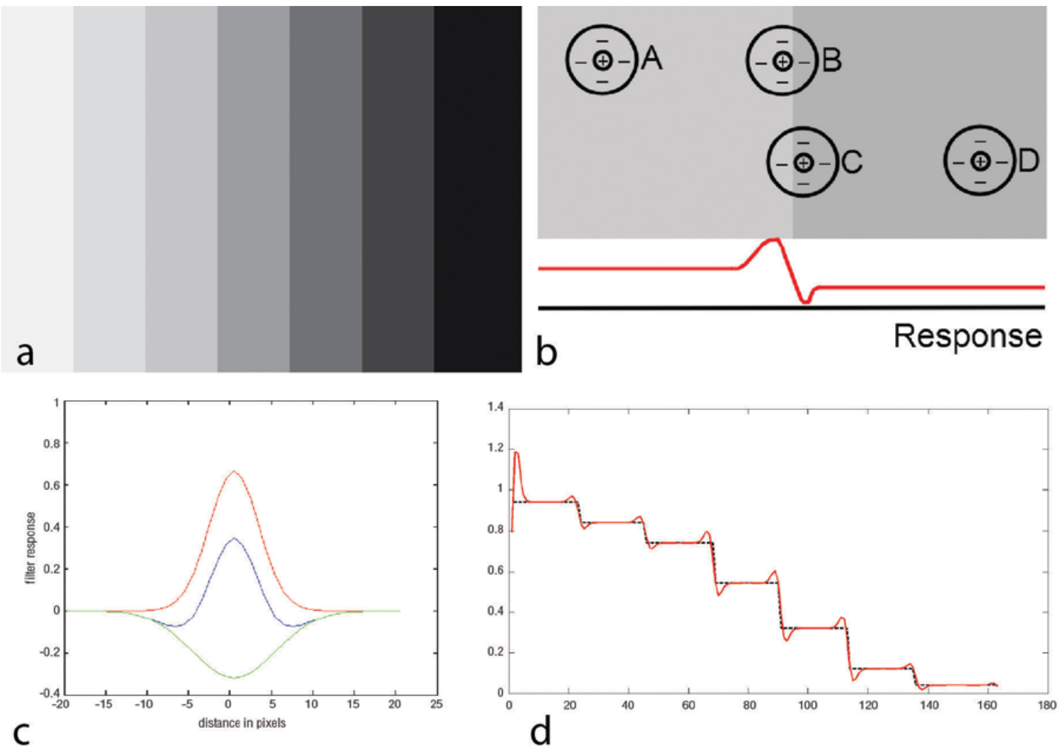



*Figure 3.16 The "Mach bands" illusion.*

*a) The pattern presented to an observer.*

*b) Next-to-edge ON-cell response.*

*c) Difference-of-Gaussians spatial filter impulse response (blue line) as a combination of direct excitation (red line) and lateral inhibition (green line).*

*d) ON-system response (red line) to the input luminance (black line) along the horizontal axis.*

hence the signal is perceived as brighter overall. In the case of position C the negative signal is enhanced by the portion of the outer zone of the field of view of the ganglion cell that results in a perceived reduction in brightness.

The Mach illusion holds for any rotational orientation, size, or line curvature (Mach rings). It can be observed over a wide range of illumination. This simple illusion illustrates how the perceived image differs from the actual image hitting the eyes retina, the difference being due to low-level processes that occur in the retina. The response of a ganglion cell can be modelled by means of a Difference-of-Gaussians (DoG) spatial filter whose impulse response is shown in Fig. 3.16 (c). It is a superposition of the results of direct excitation and lateral inhibition. Applying such a filter to the Mach bands, an output signal can be obtained, the plot of which is shown in Fig. 3.16 (d).

How is it that our visual system produces such illusions? In accordance with the principle of maximum information extraction, such processing of the observed image enhances local contrast, thus enabling enhanced perception of image details. Contrast can be defined as a difference in brightness / colour in different parts of an image. Often the quantitative value of maximum contrast in the image is assessed, that is, the relation between the maximum and minimum brightness, which is called the contrast ratio or global contrast. When considering sensor-based systems, the corresponding value is also called the dynamic range. It is calculated on the basis of the maximum and minimum distinguishable signal levels. Local contrast at a certain area of an image (referred to as spatial contrast) is characterized by the relationship of the brightness of an image element (point) to the surrounding brightness.

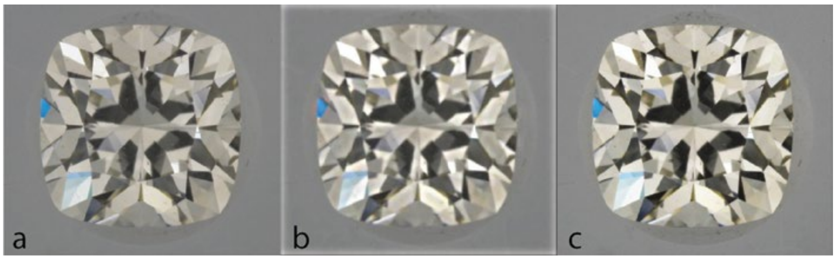



*Figure 3.17 Comparisons of a diamond image (a), enhancement of local contrast (b) and linear enhancement of dynamic range (c).*

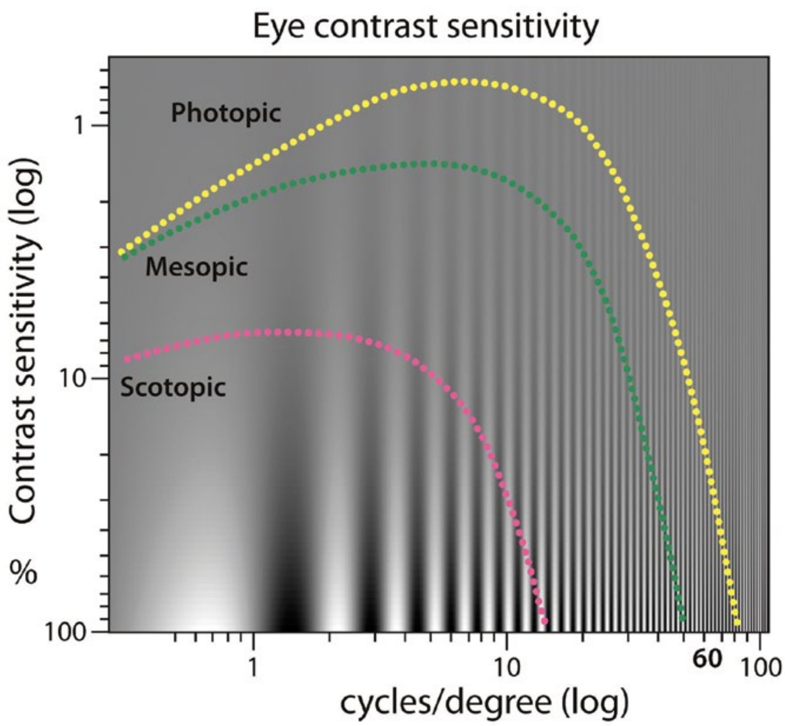



*Figure 3.18 The contrast sensitivity function (CSF) for different adaptation modes. Dotted lines reflect minimal signal amplitude needed to distinguish a sine-wave or sinusoidal pattern of different frequencies. Sensitivity is the highest in the photopic mode (yellow), somewhat lower in the mesopic mode (green), and the lowest in the scotopic mode (pink). (Source: http://www.telescope-optics.net/aberrations_extended.htm).*

The diamond image in Fig. 17(a), as an example of local contrast enhancement is shown in Fig. 17(b) after a DoG spatial filter adjustment for a medium frequency band that plays a major role in this phenomenon. The filter applied is similar to that shown in Fig. 16(c, blue line). In Fig. 17(c) a linear increase in the dynamic range has been applied. This local contrast enhancement filter makes medium-size bright facets brighter when surrounded by darker facets considerably increasing facet border contrast.

### *Contrast Sensitivity Function (CSF) and optimal virtual facet size*

Each ganglion cell is tuned to a certain size of stimulus and collectively they cover a wide range of sizes that correspond to the dimensions of real world objects. The contrast sensitivity function (CSF) represents the dependence of the stimulus perception threshold on the spatial frequency of the stimulus. This function depends on the overall distribution of ganglion cells that are tuned to stimuli of different sizes.

Over the past 50 years psychophysiologists have performed a series of experiments to measure contrast sensitivity function (Schade, 1956). In these tests, observers were asked if they saw a signal or not for stimuli of different spatial frequencies and intensities. As a result of these studies, the following conclusions were made: under well-lit conditions, the spatial sensitivity of human vision reaches its maximum within the range of angular spatial frequencies from 4 to 10 cycles per degree and decreases progressively for lower and higher frequencies, as shown in Fig. 3.18. (See Georgeson and Sullivan, 1975 for details).

The receptive field varies depending on adaptation to dark and light illumination. Therefore contrast sensitivity depends on the level of light adaptation of vision with peak functioning shifting to higher frequencies as illumination increases. The most effective range of eye sensitivity to contrast depends on the amount of illumination in the viewing environment. In daylight (photopic vision, yellow plot in Fig. 3.18), the sensitivity to higher frequencies exceeds that in dim lighting (scotopic vision, pink plot in Fig. 3.18). Briefly, photopic vision is enabled in daylight, scotopic in moonlight and mesopic in twilight. See full definitions of photopic and other vision modes in Box D. For normal viewing of diamonds, photopic vision is most important. Therefore, only those viewing conditions enabling the photopic vision are considered below.

Contrast sensitivity decreases further from the fovea centralis or central macula region of the retina. This region is responsible for sharp central vision where visual detail is of primary importance.

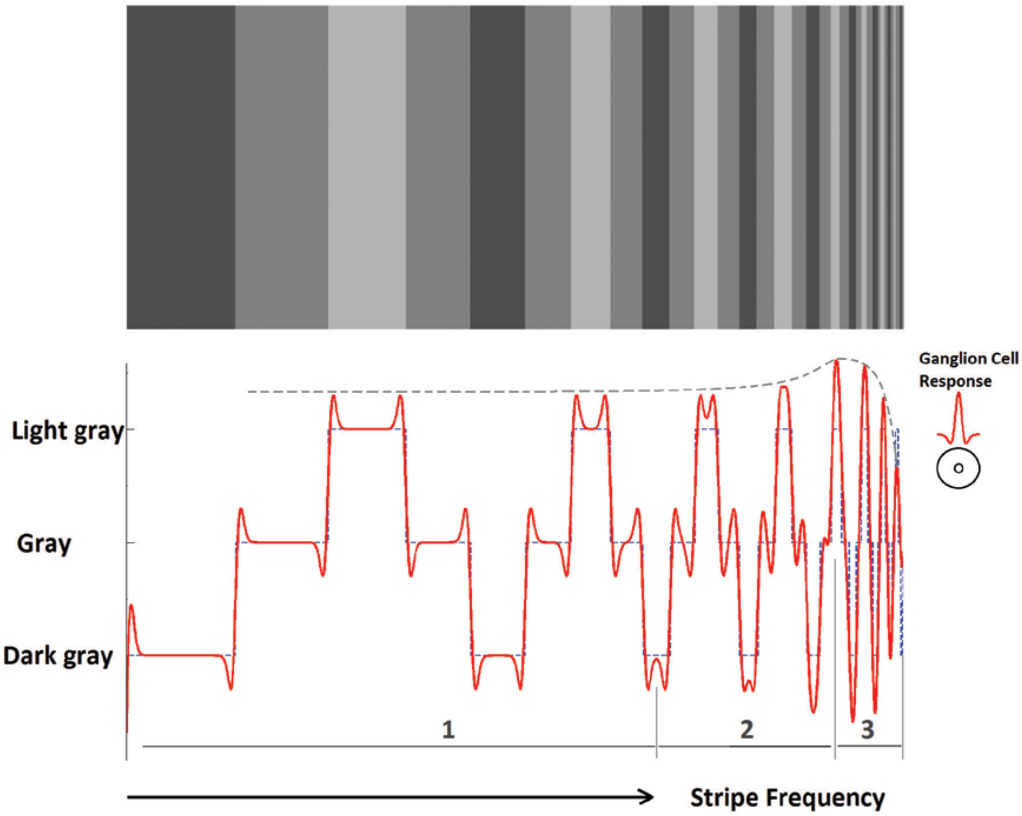



*Figure 3.19 Top: Mach's bands of 3 levels of brightness and decreasing width.*

*Right: The receptive field of a ganglion cell and the plot of its response function (see Box D).*

*Bottom: The blue dashed line is the input luminance profile of the Mach band pattern. The red solid line is a plot of the modelled response strength. The grey dashed line is the envelope of the peak values of the perceived brightness for the light bands of different frequencies.*

*Zone 1 - convergence of Mach's bands, up to a full overlapping of gradients.*
*Zone 2 - illusion weakening; an increase in the subjective brightness of the light bands.*
*Zone 3 - illusion collapse; a decrease in the subjective brightness of the light bands.*

The plots shown in Fig. 3.18 illustrate the frequency dependence of contrast sensitivity for a sine wave or sinusoidal signal. Patterns within a diamond consist of separate virtual facets divided by sharp edges. Therefore for modelling this effect with a diamond we consider how the visual system responds to square-wave signals of different frequencies, an approach better suited for diamonds than a sine wave one. For this purpose, we made a 3-band Mach pattern (see Fig. 3.19 top) and repeatedly replicated it from left to right, gradually decreasing the width of the bands. Then we modelled the operation of retinal ganglion cells with a fixed sized receptive field (Fig. 3.19 right), at a certain level of light adaptation. The red plot (Fig. 3.19 bottom) shows the model response of such cells.

Three frequency zones (marked as 1, 2, and 3) are emphasized on this plot, according to the qualitative difference in the two phenomena observed: a change in the Mach bands illusion strength and a change in the maximum perceived brightness of the brightest band.

In zone 1, next-to-edge bursts of the signal do not overlap. As the spatial frequency increases, these bursts gradually approach one another. Each band is visually divided into three parts. Adjacent bands affect the two edges, but not the centre. Their width is constant. Brightness is constant, while width decreases with increasing frequency, up to full collapse.

In zone 2, in the case when the centre of the receptive field of a ganglion cell lies within a single band, the periphery of the field inevitably overlaps with the two adjacent bands. This leads to compensation of signals for the grey level, which weakens the illusion. Signals for the light and the dark bands amplify each other, increasing the perceived brightness of the former and decreasing that of the latter. As a result, the perceived contrast increases.

In zone 3, the bands become narrower than the receptive field centre. The edge signals overlap each other, decreasing the perceived brightness of the light bands. The perceived contrast decreases as well. A further increase in the spatial frequency would result in the bands merging.

As it follows from the plot, there is an optimal band frequency, at which the illusion is strongest; "the illusory stripes occupy the largest area relative to bandwidth at the border between zones 1 and 2". This frequency corresponds to the border between zones 1 and 2. Another notable feature on Fig. 3.19 is that there is a frequency at which the perceived brightness of the light bands reaches a maximum. This frequency is at the border between zones 2 and 3.

As it can be seen from Fig. 3.19, the right part of the plot of the modelled response of ganglion cells is similar to the decay of CSF at high frequencies in Fig. 3.18. Existing studies show that the position of the contrast sensitivity maximum is the same both for a sine wave and a square-wave signal (see Fig. 3.20, source: Campbell et al, 1968). The difference between these two types of signal naturally remains noticeable at low frequencies, where the sensitivity to a square-wave signal approaches a constant level due to the permanent presence of sharp edges between adjacent bands.

There is an optimum size of a regular pattern to which human perception is most sensitive. The match of the contrast sensitivities for a square-wave and a sine-wave signal at frequencies equal and greater than the CSF maximum point enables the calculation of the optimum size range of virtual facets to create the maximum local contrast. This calculation is based on the CSF plot for the photopic conditions (the yellow line in Fig. 3.18).

Fig. 3.18 indicates that the contrast sensitivity reaches its maximum around 8 cycles per degree and rapidly decreases from about 40 cycles per degree. As far as we observed, people most often evaluate brilliance from a distance of 30-50 cm. From further away, observers usually notice scintillation and fire, but not brilliance. As it follows from the calculation shown in the formulae below, when observed from 30 cm, virtual facets

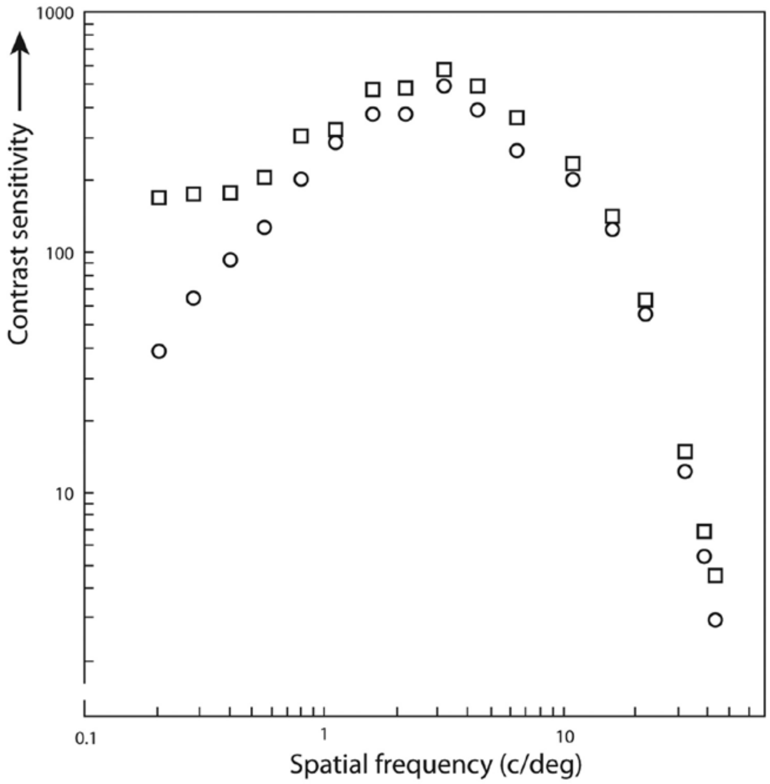



*Figure 3.20 Contrast sensitivity plots for sine-wave (circles) and square-wave (squares) signals under various adaptation conditions. Source: Campbell, 1968.*

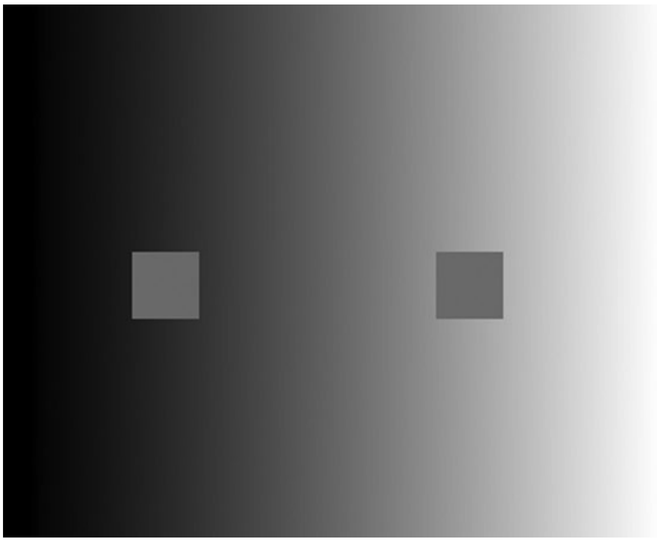


*Figure 3.21 (a) Simultaneous Contrast Illusion. Identical squares placed on a different background have a different perceived brightness.*

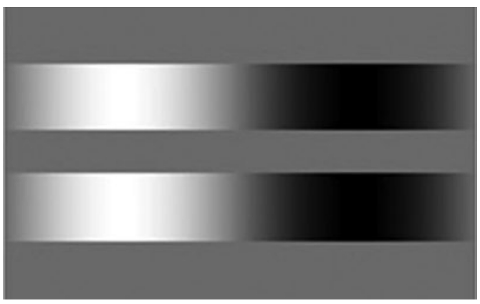


*Figure 3.21 (b) Grating Induction. Though the three background bars above and below the gradient stripes have constant physical brightness, they appear to be non-uniform.*

smaller than 0.065 mm do not contribute to contrast and brilliance, because very small facets seem too dim. It is important to realise that this result is only applicable to a regular pattern or one close to it, but not to separate bright flashes, which are still visible even when very small in size.

$$D_{min} = 300\ \text{mm} \cdot \tan\left(0.5 \cdot \frac{1}{40} \cdot \frac{\pi}{180}\right) \approx 0.065\ \text{mm}$$ [1]

$$D_{max} = 500\ \text{mm} \cdot \tan\left(0.5 \cdot \frac{1}{8} \cdot \frac{\pi}{180}\right) \approx 0.545\ \text{mm}$$

In addition, it does not make sense for the virtual facets to exceed 0.545 mm when viewed from further away, say 50 cm, as the total length of the borders at which high contrast is reached will decrease for the same or lower local contrast. The remaining area of the image will consist of uniformly coloured zones with almost zero contrast.

The two formulas above determine the minimum and the maximum effective size of virtual facets, required to achieve the highest perceived contrast. Additional reasons why virtual facets larger than 0.5 mm are not as effective will be explained in the next article the authors will present. This virtual facet size range is most effective for observing brilliance, but can be different for scintillation and fire. This data is useful for enhancing the visual contrast of a pattern when designing new cuts while taking into account additional factors, such as facet shape, oblongness, facet aggregation into bright and dark clusters, and other factors.

### *Subjective brightness, suprathreshold contrast, Weber's and Stevens' laws, Contrast and Assimilation*

The contrast sensitivity function (CSF) only describes changes in the detection threshold of a stimulus depending on its frequency. As the stimulus contrast ratio (amplitude of a signal) increases, its distinctiveness continuously increases as well. Furthermore, the perceived brightness of the stimulus depends on the following factors: the spatial frequency of the stimulus, the intensities of the stimulus and the surrounding, and the vision adaptation level. This dependence is referred to as the suprathreshold contrast sensitivity. It is clearly demonstrated in Fig. 3.21 (a) as a simultaneous contrast illusion. In some cases, this effect is strong enough to change the perception of brightness of a uniform area (Fig. 3.21 (b).

[1] The 0.5 multiplier is necessary because the flash size corresponds to half of the cycle.

In 1834, Ernst H. Weber discovered an empirical law of perception. This law states that the ratio of the just noticeable difference of the stimulus intensity *ΔI* (JND, also referred to as the increment threshold) to the intensity value I is constant:

$$\frac{\Delta I}{I}=k.$$

The constant k is called the Weber fraction. The larger the Weber fraction, the larger the change in the stimulus intensity required for an observer to notice the difference, that is, the higher the complexity of distinguishing between stimuli of different intensities. Weber's law is fulfilled at the photoreceptor level. For the retinal cones, the Weber fraction is about 0.14, while for the rods it ranges from 0.015 to 0.03 when illumination conditions are not extreme.

A follower of Weber's, Gustav T. Fechner (1860), tried to extend the law. He assumed that the perceived increment *ΔS* that corresponds to a JND *ΔI* does not depend on the perceived strength of a stimulus *S*, i.e., that it determines a linear scale of the perceived strength for a certain type of stimuli:

$\Delta S=c$, where c is an arbitrary constant.

Fechner divided one equation by the other and integrated the obtained identity, assuming that the differential relations are fulfilled on the whole segment of values. As a result, he derived the following general form for the extended law:

$$S = \frac{c}{k}\ln\frac{I}{I_0},\ I_0 \text{ is another constant.}$$

The law derived by Fechner was supposed to be the same for all sensory systems. In the particular case of vision, this law states that the perceived brightness changes as the logarithm of the light stimulus intensity. However, it was later discovered that Fechner's law is not valid for a large enough range of stimulus intensities.

Assuming that the invariant constant is not the absolute, but the relative value of the perceived increment (Brentano, 1874), we obtain the following equation:

$$\frac{\Delta S}{S} = c,$$

which, in the aggregate with the Weber's law, leads to

$$\ln S = \frac{c}{k}\ln\frac{I}{I_0}.$$

Taking the exponents of both sides of this equation, we obtain the following power law:

$$S=bI^a,$$

where a=c/k is Stevens' exponent, while $b = I_0^{-\frac{c}{k}}$. Both these values are constant within a single modality.

Stanley S. Stevens, who considered the above formula to be a universal law of perception, made a lot of experimental research to calculate the exponent constant for different sensory organs and different types of physical impact (Stevens,1957) resulting in the Stevens' power law. A more extensive research on psychophysiological scales and laws can be found in (Krueger, 1989). To date, however, it is assumed that when vision adaptation conditions are fixed, the perception of brightness is governed by the Stevens' power law.

When developing measures for optical properties of a diamond, it is necessary to know the Stevens' exponent values for different factors affecting human perception of these properties. For instance, to compare the effect of a smaller brighter flash and a larger dimmer flash on diamond scintillation, one should understand how the size and the intensity of a flash are scaled in human perception; proper scaling of all the factors that have an effect, taking them into account simultaneously, and arriving at an overall grade, which is linear in human perception.

Human vision is capable of adapting to a very broad range of illumination, keeping the perception of objects close to constant. A well-known postulation is that human vision maintains a relatively unchanged perception of objects even though there may be changes in the intensity of illumination and in its colour, the position and the orientation of light sources, and other factors. In a broad sense, this feature of vision is called colour constancy. A well-known example of a manifestation of this kind is the so-called Adelson's illusion (Fig. 3.22). The essence of this illusion is the following: white (B) and black (A) cells of a chess board have the same objective brightness and when the white cell is shaded by an external object we still perceive the shade of the cell B as white, close to that of the non-shaded white cells.

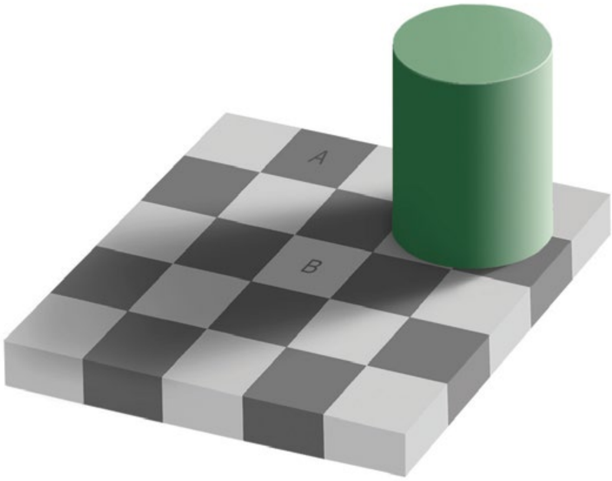



*Figure 3.22 Adelson's Illusion is a particular case of colour constancy: both squares A and B are identical shades of grey. If you do not believe this, cut two well-placed holes in a piece of paper and hold it over the A and B (http://persci.mit.edu/gallery/checkershadow).*

Land and McCann, 1971 proposed the idea that there is a threshold for detecting variations of lightness, which allows the visual system to detect edges and to estimate their contrast, while neglecting small variations in the lightness gradient. This idea is an attempt to explain the property of colour constancy by means of not global but local operations. It underlies the Retinex theory developed by the same authors. However, it is already known now that the Retinex theory cannot completely model the visual perception of a scene under various illumination conditions (Hurlbert and Wolf, 2002). There are grounds to suppose that the reason for this is that the colour constancy mechanism employs not only low-level processes of adaptation and spatial contrast, but also quite high-level processes occurring in the human brain (Hurlbert and Wolf, 2004), such as object separation and memorizing its colour.

Contrast enhancement in human vision makes some objects look brighter than a uniform area of the same intensity (Fig. 3.23 a). In this case, over-ranging of the natural dynamic range of the image source (a monitor or a paper sheet) creates an illusion of glow or highlight (see Fig. 3.23 b), where the centres appear to be brighter, an illusion enhanced by means of coloured rings. Similar inverted effects may create an illusion of subjective darkness or light absorption. When such effects take place, the perceived dynamic range of image brightness, that is, the ratio of the maximum and the minimum perceived brightness, becomes larger than that for a uniform gradient image having the same intensity limits (under the same illumination conditions). It is also interesting that in similar static images, scintillation and brilliance effects may arise (Fig. 3.23 d) due to the observer's eye movements. These illusions cannot be explained only by the action of the eye retina. Apparently, they utilize specific neurons of the brain cortex, which specialise in detecting line ends (see the "High-level effects of perception" section for more details).

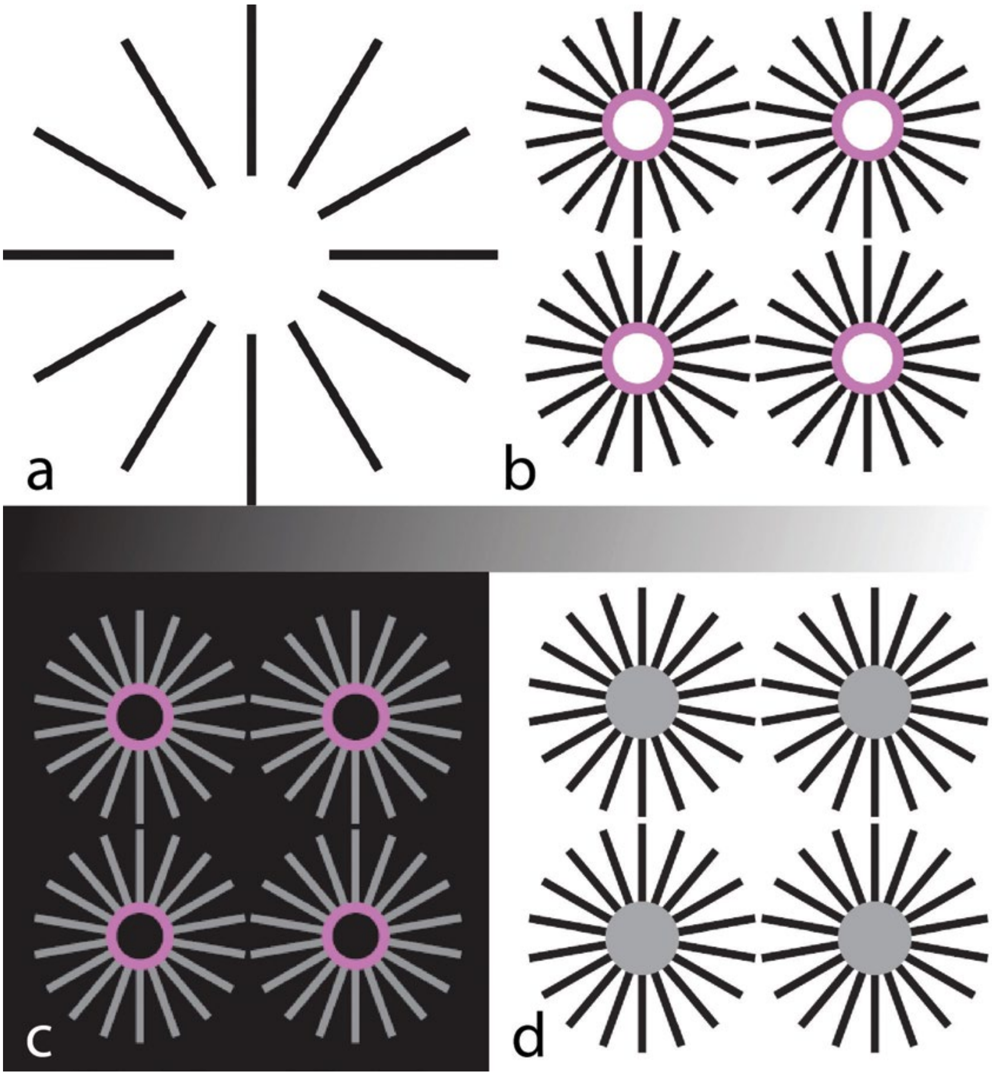



*Figure 3.23 a) Ehrenstein illusion; b) Anomalous induction of brightness; c) Anomalous induction of darkness; d) Scintillating lustre [source: Werner et al., 2008].*

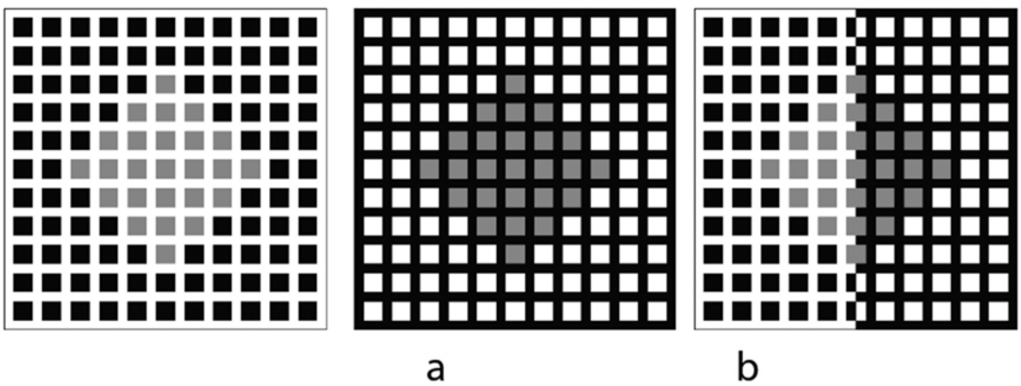



*Figure 3.24*

*a) Dungeon illusion as an example of assimilation. Though the grey squares of the two patterns have the same brightness, the left squares look darker than the right ones.*

*b) Two halves of images joined together to prove the shades of grey are identical.*

In Fig. 3.24, the grey squares surrounded by white stripes look lighter than the same grey squares surrounded by black stripes. The local contrast effect, which enhances the difference between an image element and its surrounding, predicts inverse behaviour of the perceived brightness. This effect is called assimilation (see, for example, McCann and Rizzi, 2011). The assimilation effect makes the brightness of the image element closer to that of the surrounding, almost the opposite effect to the local contrast effect displayed in Fig. 3.21 (a, b).

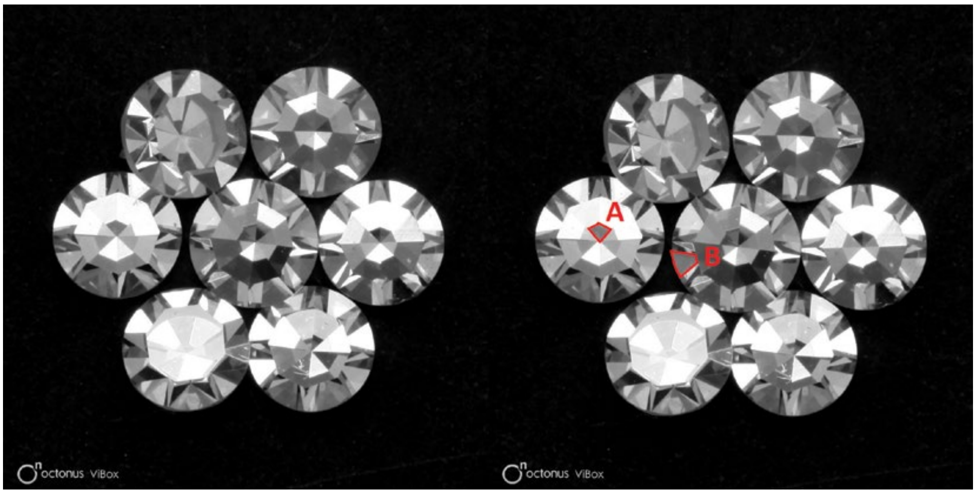



*Figure 3.25 The facets marked A and B on these single cut diamonds are the exact same shade of grey. Facet A, surrounded by bright facets, appears to be darker than the facet B because of contrast.*


*Figure 3.26 Examples of assimilation. A pyramid of scales for two clusters: full-cut at left and single-cut at right. Both pictures of clusters have exactly the same average intensity (52 of 255). At a certain scaling the left cluster looks significantly brighter than the right one due to assimilation (the larger bottom image is best when seen from further away, e.g. 2-3 m). An optimal scaling for the effect could vary due to size of the medium and the viewing distance.*


*Figure 3.27 Examples of interaction of flashes seen by the left-eye and right-eye of a diamond in the course of forming the resultant image. The numbered frames mark some groups of closely spaced flashes seen by each eye. For convenience, the framed areas are combined in pairs in the right box.*

When viewing a diamond, the effects of contrast and assimilation develop at the level of separate virtual facets and their groups. Both the contrast and the assimilation may increase the perceived brightness of separate regions and/or the overall image of the entire diamond. Some real world examples are shown in Fig. 3.25 and Fig. 3.26. Fig. 3.25 illustrates the influence of contrast on perceived brightness of a diamond's facet. Fig. 3.26 reveals how perceived brightness of the whole diamond could be affected by the assimilation effect. Assimilation affects brightness of the left cluster more because of longer total border lengths of the bright flashes. To be more exact, the effects of contrast and assimilation work together in this case, affecting the perceived image to different extents at each of the five scales.

The spatial effects of contrast and assimilation are caused by complex psychophysiological perception processes. Up to now, researchers have made a large number of psychophysiological studies and have proposed various models to explain their interaction (see Blakeslee and M.E. McCourt, 1999; Robinson et al., 2007; Barkan et al., 2008; Otazu et al., 2008; Anderson and Winawer, 2005; Economou et al., 2007; Ross and Pessoa, 2000). The results of these studies enable the development of rather general numerical models for computing perceived brightness. These models describe most illusions observed in real life.

The spatial pattern of every diamond cut is unique and important for grading its optical properties. To achieve the highest values of the perceived brightness of a diamond, its image should not be monotonously bright (this would maximize the objective brightness only). The optical illusions discussed above vividly demonstrate that the presence of darker regions can considerably increase the perceived brightness of brighter regions adjacent to them. However, the darker regions should not be too large. If so, the assimilation effect would create a large darker zone, which decreases both the effective area of the diamond and its overall brightness. Diamond is unique in the fact that its image may have a very large range of brightness, the maximum brightness approaching that of the illumination sources. Furthermore, darker and brighter regions may rapidly alternate, thus creating complex patterns. Such an image has a great spatial contrast, which is further enhanced by the human vision system to play an important role in forming the subjective sensation of Brilliance.

## *Binocular vision effects*

Under binocular viewing conditions, diamonds show an even wider variety of perceptual phenomena than in the case of monocular images. Binocular perception of diamonds, unlike that of most other objects, is not limited to stereoscopy (perception of depth). The pattern of a diamond is so complex that it is very difficult to perceive it as a single-piece 3D object. In this case, binocular fusion and binocular rivalry effects play an important role.

Binocular fusion (also referred to as binocular summation) is an effect that enhances the contrast of an object observed with both eyes simultaneously. One of the traditional ways of modelling binocular contrast perception is the probability summation of contrast responses of each eye. For the simplest case, this can be expressed by the formula:

$$C_{STEREO} = \sqrt[p]{C_{LEFT}^{p} + C_{RIGHT}^{p}}$$

where C is the contrast ratio and p is the power index that, in accordance with the results of various experiments, lies within the range $2 \le p \le 4$. This formula is proven experimentally under the conditions of absence of opposite contrast response of the eyes, whereas the condition of competition of the eyes has to be taken into account separately. So far, experts in visual perception have come up with fairly complicated models that take into account many factors of contrast perception of stereo visual signals (Meese et al., 2006). We make considerable use of the results of ongoing stereo vision modelling research for developing our algorithms or metrics for appraising the visual attributes of diamonds.

The binocular summation of contrast drastically affects not only the Brilliance but also the Fire shown by diamonds. Our studies have demonstrated that in ViBox movies of the round brilliant cut diamond MSSR13, important colour flashes often appear simultaneously in both the right and the left channel and overlap by a relatively large area. This phenomenon is directly associated with the presence of 'lingering' virtual facets. In such a facet, the same flash can be observed by both eyes. In this case, fusion often occurs, making the observer see only one flash. For such cuts, the increase in the flash count with a switch from mono to stereo movie grading is smaller than some other cuts that may have almost double the flash count when seen in a stereo movie.

However, when observing a diamond, a special effect discussed in the Section 3.2 Stereo Vision, often occurs due to the fact that the two observers' eyes form two totally different images. While comparing these images, the brain frequently faces strong contradictions that give rise to so-called binocular rivalry (Wolfe and Franz, 1988). A special kind of this rivalry occurs when one eye sees a dark image and the other eye sees bright image in the same area of space. An observer sees a sequence of rapidly flickering alternating of images. This flicker often brings about the sensation of a lustrous surface, called binocular lustre (again, see Wolfe and Franz, 1988). The binocular lustre is best noticed when one eye sees the object as brighter than the background, while the other eye finds the object darker than the background. We believe that binocular contrast and the phenomenon of binocular rivalry play a major part in the perception of Brilliance. We conducted a series of tests to prove this. The results of these tests are discussed in Section 3.2 Stereo Vision.

The flicker caused by binocular rivalry arises as follows: at any specific time, stimuli from one or the other eye dominate in perception, suppressing the other. The time interval of continuous domination of one of the stimuli is called alteration. In some cases, the domination becomes complete, that is, the alteration of one of the stimuli becomes very long. The state of complete domination is similar to binocular fusion in the fact that there is no switching between images but there is a prominent stimulus lasting for a long time. The difference between the complete domination and fusion is in the fact that for a specific area of space all the information comes from one eye, while the information from the other eye is fully ignored. In particular, this occurs in the example described in Section 3.2 Stereo Vision, when observing a stereo image of a diamond with a highlight in one of the channels.

An increase in the contrast of one of the competing stimuli increases its domination time and decreases its suppression time (Levelt, 1966). Thus, stronger flashes most likely suppress weaker ones. The domination time is also affected by context: objects get a preference over backgrounds and common objects get a preference over unusual, for example a normally oriented face over a rotated face (Engel, 1956; Yue and Blake, 1992). Besides, assimilation also promotes domination (Fukuda and Blake, 1992; Campbell et al., 2004), that is, in some cases the flash chosen from two, is the one better matching the surrounding. An important factor is grouping, that is, merging of similar images from different eyes in a single alteration (Alais and Blake, 1999; Sobel and Blake, 2002). This means that closely spaced similar flashes will most likely be perceived simultaneously (in a single alteration), no matter in which eye they appear.

Fig. 3.27 shows a single frame of the diamond MSSR13 movie, illustrating zones of overlapping flashes. Fusion takes place in zones 1 and 3 as flashes from the left and the right eye merge. Binocular rivalry arises in zones 2, 4, and 5 and at any specific time, the observer perceives a portion of the image which is viewed by a single eye only. In example 2, the left stimulus dominates most of the time, while in example 5 the right one is dominant. In example 4, complete domination of the orange flash is observed. This is because its contrast exceeds that of the purple one.

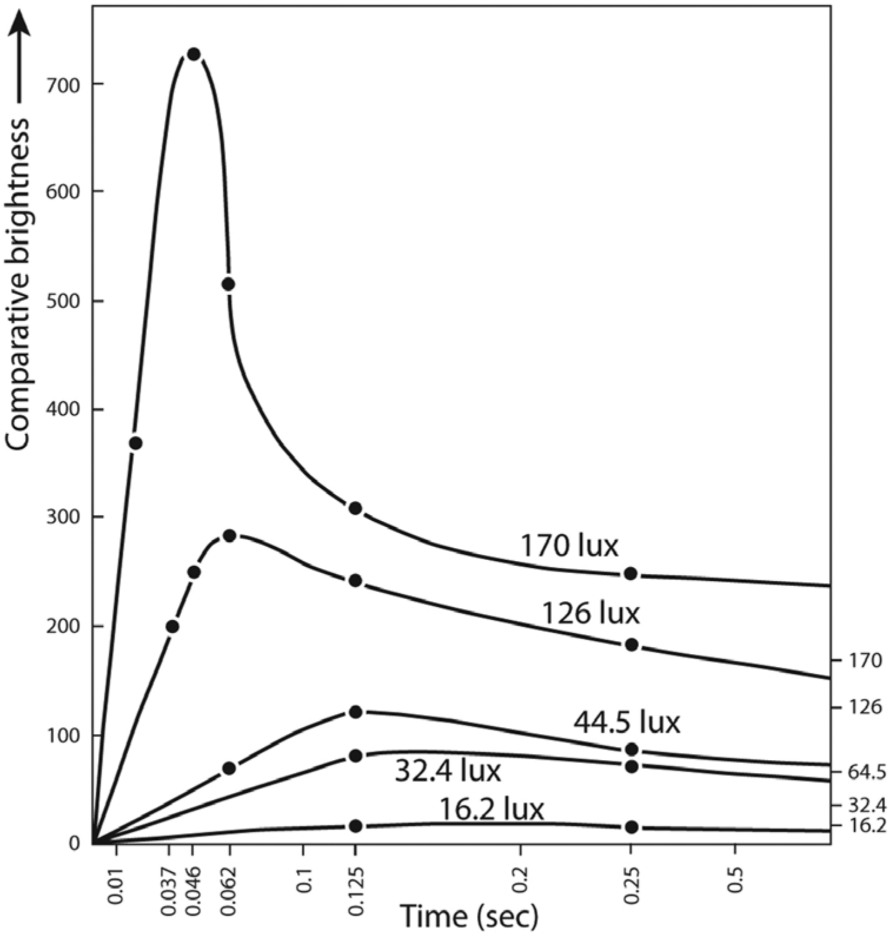



*Figure 3.28 Apparent brightness of flashes with various luminance, as a function of flash duration. Source: (Broca and Sulzer data from Kalloniatis and Luu. WebVision).*

## *Dynamic Contrast and Temporal Effects*

When observing a static diamond, we see practically no "life" in it: the brilliance effect is highly damped, while any static flashes do not appear very attractive. One of the reasons for this is the absence of dynamic contrast. Dynamic contrast is associated with the effect of enhancement of the perceived brightness with temporal changes of the observed pattern. One of its manifestations is the Broca-Sulzer phenomenon of apparent amplification of a short-duration flash (Fig. 3.28, Kalloniatis and Luu, WebVision). The results of experiments with a blinking diode published in this paper show that when the flash duration is from 50 to 100 ms, the diode seems much brighter than when in continuous operation.

This phenomenon is caused by a rapid growth of excitation of retinal neurons at the sudden appearance of a signal, which is known as overshooting. It suggests a mechanism of how to increase scintillation of a diamond: it is advisable for the diamond cut shape to gather rays coming at different angles in a single crown area. Such cuts will show stronger flash dynamics with small natural rocking of the diamond, making the flashes look apparently brighter.

Dynamic contrast greatly affects not only bright flashes, but low dynamic range images as well, this fact being confirmed by a variety of studies of spatio-temporal contrast (Burbeck and Kelly, 1980; Kalloniatis and Luu., WebVision). There are several facts known about the processes involved in perception of dynamic images.

To detect light flashes, one by one, an appropriate integration time (10-15 ms for cones) is required (Kalloniatis and Luu. WebVision). If the signal remains constant with time, the response to it becomes compromised. This feature is caused by physiological processes of neural adaptation, which are described in (Schmidt and Thews, 1989). The above two processes are responsible for the band-pass temporal response of vision, which passes middle frequencies, but dampens low and high frequencies. This is seen in the bell-like shape of the plots of Temporal Contrast Sensitivity Function (TSF) for a flickering signal under different light adaptation conditions, shown in Fig. 3.29. In the case of photopic vision, our perception is most sensitive to signals blinking at a frequency of 15-20 Hz, with a dramatic decay in sensitivity occurring around 60 Hz.

In summary, Temporal Contrast Sensitivity greatly affects dynamic pattern contrast, and therefore Brilliance, while the Broca-Sulzer effect has a big influence on perception of flash brightness, and therefore Fire and Scintillation. The human perception of short and long-lived flashes is also influenced by a number of high-level effects as follows.

## *High-Level Effects of Object Perception*

In addition to the above-mentioned effects that are associated with low-level mechanisms of the human visual system, high-level mechanisms of perception must be also taken into account when evaluating the optical properties of diamonds. We call the high-level effects those occurring not at the level of individual receptors or retinal cells but at the

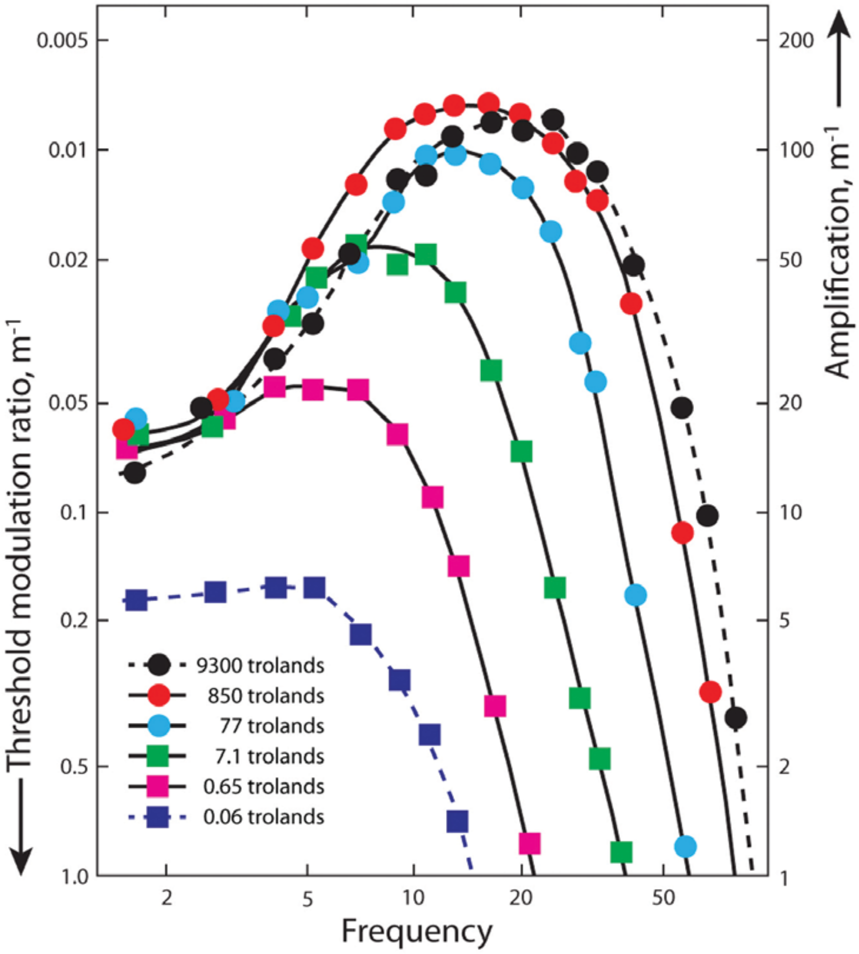



*Figure 3.29 Temporal contrast sensitivity function (TSF) for various light adaptation conditions. Background retinal illuminance is measured in trolands[2]. Kelly's data, source: Kalloniatis and Luu. WebVision.*

brain level and solving such problems as object detection and analysis or phenomena evaluation (both qualitative and quantitative). We do not claim a thorough review of these effects but discuss some of them, which are, in our opinion, important but not so evident.

The Ehrenstein illusion, discussed earlier and shown in Fig. 3.23, is an example demonstrating perceived brightness enhancement. The key to this illusion is not in the retina but in the human brain cortex (Spillmann et al.,1976). A possible explanation of the illusion lies in the answer to two questions: "Why do we see a circle?" and "Why does this circle look brighter than its background?"

From an evolutionary point of view, human vision is capable of completing missing parts of boundaries in order to identify real-world objects, which are partially or completely screened by other objects: for example a man needed to be able to identify a sabre-tooth tiger running through dense forest, only being partially visible for milliseconds. In the case of the illusory circle in Fig. 3.23, black lines appear to be in contact with something. Accordingly, the observer's brain supposes the presence of an object, reconstructing its shape from the information available (Kanisza,1979). The results of studies performed let us assume (Werner et al., 2008) that this mechanism is realised by means of special end-of-line detectors (end-stopped neurons have been found in the visual cortex), which excite signals orthogonal to their direction. After an object is extracted, its perceived brightness starts forming. The perceived brightness of the object is its objective brightness shifted in the direction opposite to the brightness of the lines.

End-stopping neurons enhance local contrast so that the border of the white illusionary circle appears brighter. When we visualise the circle as a whole object and evaluate its integral brightness, the circle diffuses so that it looks brighter than the background.

For the evaluation of objective brightness, studies have revealed some rules for simple image assessment. However, the answers for complex image mechanisms for perception of brightness and contrast are still pending. It is evident that besides the eye retina, the brain cortex is also an active player in the team involved in visual signal processing and the mechanisms operating are still under study. Therefore, there are a number of hypotheses for the description of high-level visual processes.

[2] 1 troland = 1 cd/cm^2 is equal to retinal illuminance produced by a surface whose luminance is one nit (cd/m^2) when the apparent area of the entrance pupil of the eye is 1 square millimetre (http://en.wikipedia.org/wiki/Troland).

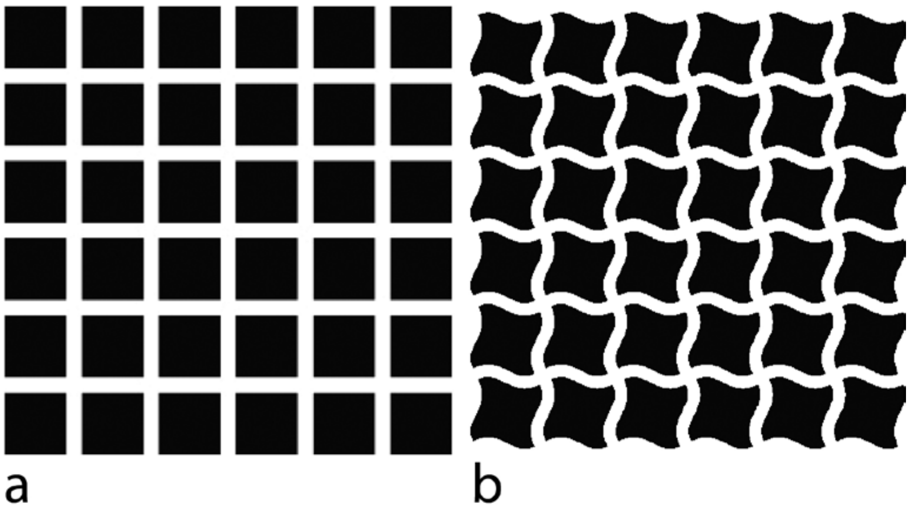



*Figure 3.30 a) Hermann-Hering grid illusion. Illusory dark spots appear at the intersection of the white stripes, except for the crossing where the sight is fixed. b) Wavy grid. There are no longer dark spots at intersections disproving the classical explanation of the grid illusion.*

Another example of an illusion, which cannot be fully explained at the retinal level only, is the Hermann-Hering grid illusion presented in Fig. 3.30 (a). The observer sees dark spots at the intersection of the white stripes, except for the crossing where the sight is fixed. The first explanation of this illusion postulated that lateral inhibition is enough to cause the illusion. As in the case of the Mach illusion, the ganglion cells located on the crossings are inhibited stronger that those located on the stripes. The absence of a dark spot at the fixation point is caused by a small size of the receptive field within the foveal pit. However, this explanation has the following contradictions:

1) the illusion disappears if the grid pattern is wavy curved, as it is shown in Fig. 3.30 (b);
2) the illusion gets much weaker if the grid is rotated.

These observations led to the conclusion that although the retinal mechanisms are necessary to explain the grid illusion, they are not sufficient.

An alternative explanation of the grid illusion was proposed in Geier et al., (2008). The authors have studied various grid shapes to show that the straightness of the white stripes is more important for the illusion to occur than the lateral inhibition. An example of a wavy distorted grid that shows no dark spot illusion is shown in Fig. 3.30 (b). The dark spots that should appear according to the lateral inhibition concept are not seen at the crossings of the distorted stripes. A mechanism that keeps the illusion for the straight grid and disables it for the distorted grid follows from a so-called radiating edge hypothesis. The hypothesis assumes that the dark crossings appear because the white stripes appear to radiate light. Geier (2008) proposed a three layer model to explain these illusions. His hypothesis is that in addition to the illusion processing sensory layer, there is also an edge-detector layer, as well as a diffusion layer. At any point on a white stripe, the edge detectors determine the direction of the stripe and the vector normal to it. This is being accomplished through selection of responses of oriented receptive fields in the brain cortex. An edge detector forms a bipolar signal that extends darkness towards the adjacent black squares and brightness towards the white stripe centre. The diffusion layer distributes the signal over the whole image, the signal strength decreasing with the distance covered and increasing when it passes through co-directional elements. Thus, for the straight grid, the signal is repeatedly amplified everywhere except for the crossings, while there is no such amplification for the distorted grid.

A scintillating grid illusion implies that dark dots seem to appear and disappear within white circles during line-of-sight movement (Fig. 3.31a). To enable this illusion, in addition to lateral inhibition, the dark dots appear due to the signal fall-off, in comparison with the previous saturated signal (see Fig. 3.31 b) and line straightness and orthogonal structure (as shown in Fig. 3.30 b). Saccadic eye movement, quick, simultaneous movements of both eyes in the same direction, with fixation at white circles is obligatory. If the line-of-sight is fixated at a single point for a considerable time, the black dots disappear. Also as in the case of the Hermann-Hering illusion, the scintillating grid illusion collapses if the grid is wavy or distorted, and the shade of the dark dots shifts towards that of the background, regardless of the intersection shade.

Summing up the observations of psychophysiologists, we list the most important factors for the scintillating grid illusion to occur:

1. saccadic eye movement
2. grid orientation
3. presence of several elements to enable line-of-sight jumps (at least, a 3x3 grid), no scintillation occurs at an isolated intersection (Schrauf et al 1997);
4. straightness of the lines that build up the grid
5. brightness of the background.

The eye's retina is the primary player in the mechanism of lateral inhibition, enhancing variations of brightness and the basis of vision is contrast perception as discussed earlier. However, as we have shown, low-level contrast mechanisms of visual perception are not able to explain all of what we 'see'. Grid illusions are a good example of how high-level mechanisms change visual perception.

### *Occupancy Model*

It is postulated that when a human observer makes a quick guess at the number in a set of objects (referred to as perceived numerosity), he/she makes a conclusion based on the approximate area occupied by the objects rather than the number of the objects in itself. This mechanism is described by the so-called "occupancy model" (Allik and Tuulmets, 1991 ), as illustrated in Fig. 3.32.

In particular, the model explains the origin of the regular-random numerosity illusion (Ginsburg, 1980), which implies that when some objects are grouped spatially, their perceived numerosity decreases as compared to when they have uniform distribution as shown in Fig. 3.33.

The above-described phenomenon of perception arises when an observer tries to quickly estimate the numerosity of a large number of objects. In the case of a diamond, it is applicable to the estimation of the numerosity of flashes produced by a diamond, in evaluating effects such as Scintillation and Fire. Taking this phenomenon into account supposes that diamonds with a more uniform distribution of flashes would appear to have more flashes than stones with clusters of closely-spaced flashes.

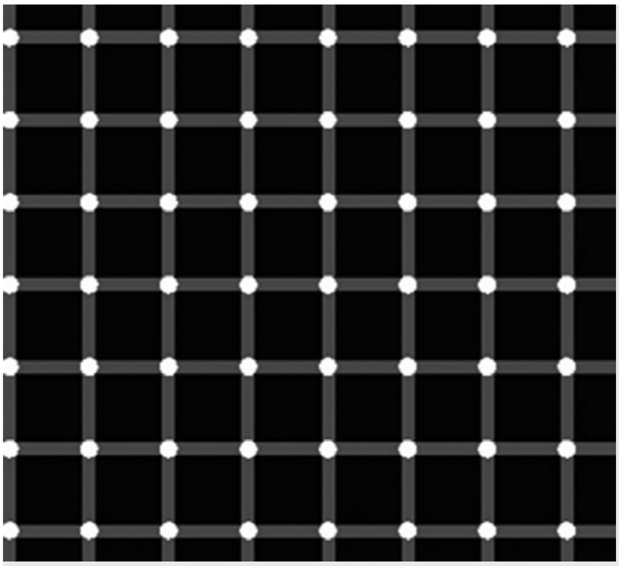


Figure 3.31 a). Scintillating grid illusion. Dots or circles flicker from white to black at the intersections as you move your line of sight.

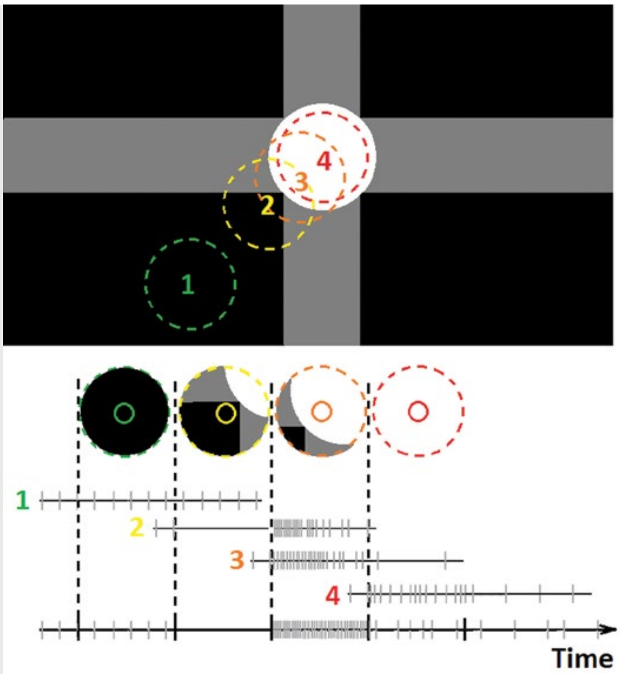



Figure 3.31 b). Illustration of a ganglion cell response at fast line-of-sight movement. The ganglion cell moves from position 1 to position 4. The graph below shows independent responses for each position along with their superposition (as functions of time). At the transition between positions 2 and 3, the signal coming from the excitation of the receptive field (RF) centre is amplified due to preceding lateral inhibition. After that, the signals are again damped by lateral inhibition, the impulse repetition rate abruptly decreases, and a sensation of reduced brightness arises.

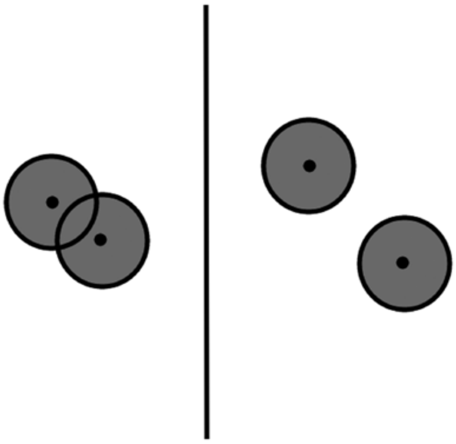


Figure 3.32 Occupancy model (Allik and Tuulmets,1991) illustration. Dots are hypothesized to occupy a region of radius R. Perceived numerosity is determined by the total area occupied by the dots. When dots are closer than 2R, their occupancy patches overlap, resulting in lower perceived numerosity.

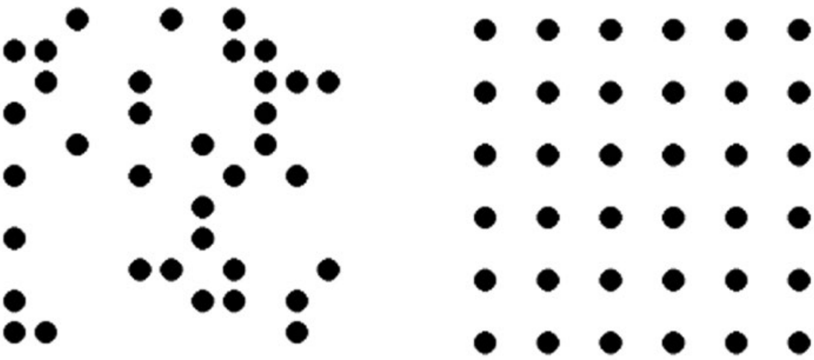


Figure 3.33 Regular-Random Numerosity Illusion. Both sets of dots contain 36 items. However, the right set appears to most people as more numerous due to its regular arrangement (from Beran, Michael J., 2006).

### After Effect (Memory) Model

When viewing a video stream with appearing and disappearing objects, a human observer does not localize objects precisely in time. After an object disappears, visual memory mechanisms keep the sensation of the presence of the object within that area for some time. The mechanisms of residual effects are classified into visible persistence (retinal or cortical) and informational persistence (Coltheart, 1980). We are basically interested in the latter, since it has longer characteristic durations and does not have an oscillating nature. The typical duration of this effect, known as the 'iconic memory', is limited to 1 second, according to most studies (Sperling, 1960).

The effect of a short-term sensation of the presence of an object which has already disappeared matches well with the occupancy model generalization proposed in Allik and Tuulmets, 1993. In this paper, the model is generalized to the case of a spatio-temporal sequence of object images and proved by appropriate experimental data.

In the study of diamond, the stimulus aftereffect model is applicable to video streams of gems showing such attractive visual effects as flashes. Thus we should consider too many flashes in the same part of a diamond that are also close together in time as a negative effect.

The most attractive diamond, therefore, should have flashes that appear regularly and disappear within different areas of the diamond as it rocks. This meets the above criteria for good spatio-temporal distribution of flashes creating the sensation of a very strong "life" and "sparkle" displayed by a diamond. The question of the optimum duration of flashes is still pending, however there are some relevant studies as discussed below.

### Flash Competition-for-Attention Model

An observer's short term working memory has limitations (Baddeley, 1987). In the context of vision, there is a theory that the visual perception process comprises creating, modifying, and deleting so-called "object files" (Kahneman et al., 1992). This work proposes that only 3-4 such files can be simultaneously supported, corresponding to the number of objects that can be tracked and kept in attention.

The following conclusions stem from this theory:

- In the presence of large bright flashes, small and/or dim flashes attract much less attention or even remain unnoticed.
- The appearance of a new flash promptly attracts attention due to an abrupt increase in contrast (overshooting effect). This effect has strong experimental evidence. A relevant conclusion in (Cole et al., 2005) states that an old object with abruptly changed colour attracts much less attention than a new object. Therefore, a colour change in a flash can be considered as a long-term static object (see the Section 3.1 Brilliance, Scintillation and Fire).
- The attention attracted by a long flash gradually gets weaker due to vision adaptation and a decrease in the perceived brightness of the flash. This statement is a logical consequence of the fact that recently appearing objects dominate an observer's attention. In (Davis and Leow, 2005), there is experimental evidence indicating that it's extremely difficult to find static objects among similar objects that either blink or change their intensities. At the same time, a static object that strongly differs from the surrounding (for example, a static dark zone among a large number of blinking flashes) can be found rather easily.

These considerations are important for correct evaluation of human perception of separate flashes and consequently for correctly calculating their weights when grading the performance of a diamond. On the one hand, the integral effect of a long flash on the human perception is less than that of a series of shorter blinking flashes. On the other hand, if diamond cut only produces very short flashes, the speed of the visual system response and the information analysis in perceptual centres cannot completely process the input data, resulting in a loss of information on the size, the colour, or even the very existence of certain flashes.

The phenomena discussed above, such as the Broca-Sulzer effect, the after-effect of a flash, and the effect of gradually decaying attention attracted by a flash, greatly increase the relative importance of short flashes for grading scintillation and fire performance of diamonds. Our experience from movies of diamonds suggests that the ratio of short and long flashes of different cuts varies considerably. This means that taking into account these phenomena for modelling human perception, strongly affects the relative performance grades of diamonds of different cuts.

### Summing up the current knowledge discussed in this section:

1. Human perception is a complex mechanism involving processes occurring in both the eye's retina, and in the brain cortex. The science of human vision and perception provides us with a considerable amount of information, but the complexity and unresolved issues make development of metrics more, not less, complicated. Using this information we can better understand what the observer sees when watching a diamond. It can be used for modelling these processes and formally taking into account the features of visual perception when developing diamond performance grading systems.
2. Features of the human vision allow subjective enhancement of the brightness and the contrast of a diamond image. Complex dynamic and binocular mechanisms of vision sometimes strongly distort the objective information coming from the object, up to creating illusions. This knowledge fundamentally changes our comprehension of brilliance, scintillation and fire, because all these phenomena inherently involve visual illusions.
3. Taking into account this knowledge allows for development of new high-performance cuts for diamonds. For instance, when the optimal properties of contrast sensitivity are known, it is possible to design and optimise the cut's virtual facets size to be best perceived. Taking into account Stevens' power law enables metric evaluations for subjective brightness and to develop other grades as well. The knowledge of binocular rivalry allows developing new diamond cuts with enhanced binocular contrast.
4. To achieve an accurate estimation of the fire and scintillation performance of a diamond based on video recordings corresponding to human perception of these effects, the following factors must be taken into account:
   - number of flashes
   - colour of each flash (brightness and saturation), brightness of a surround
   - size and shape of each flash
   - duration of each flash
   - spatial, temporal and binocular distribution of flashes.

Each of these factors should be considered in models corresponding to the above-discussed principles of operation of human perception.

*Box D: Physiology of vision*
*Visual mechanisms of local contrast*

The retina of the human eye consists of a few layers (Fig. 3.34). Three primary layers (photoreceptors, bipolar cells, and ganglion cells) provide forward signal transmission. Two secondary layers (horizontal and amacrine cells) provide a horizontal exchange of signals (Kolb H. WebVision).

Two types of photoreceptors, light-sensitive rods and colour-sensitive cones, respond to the light hitting the retina, generating an electric potential. The second layer consists of bipolar cells. There are two types of these cells: an on-bipolar cell generates an impulse when there is a signal from the corresponding receptor, while an off-bipolar cell does so when there is no signal. A horizontal cell connects a bipolar cell with several photoreceptors and provides level adjustments for signals coming from the receptors. The bipolar cells are connected to ganglion cells, either directly or through adjacent amacrine cells capable of integrating and modulating the signals from the bipolar cells.

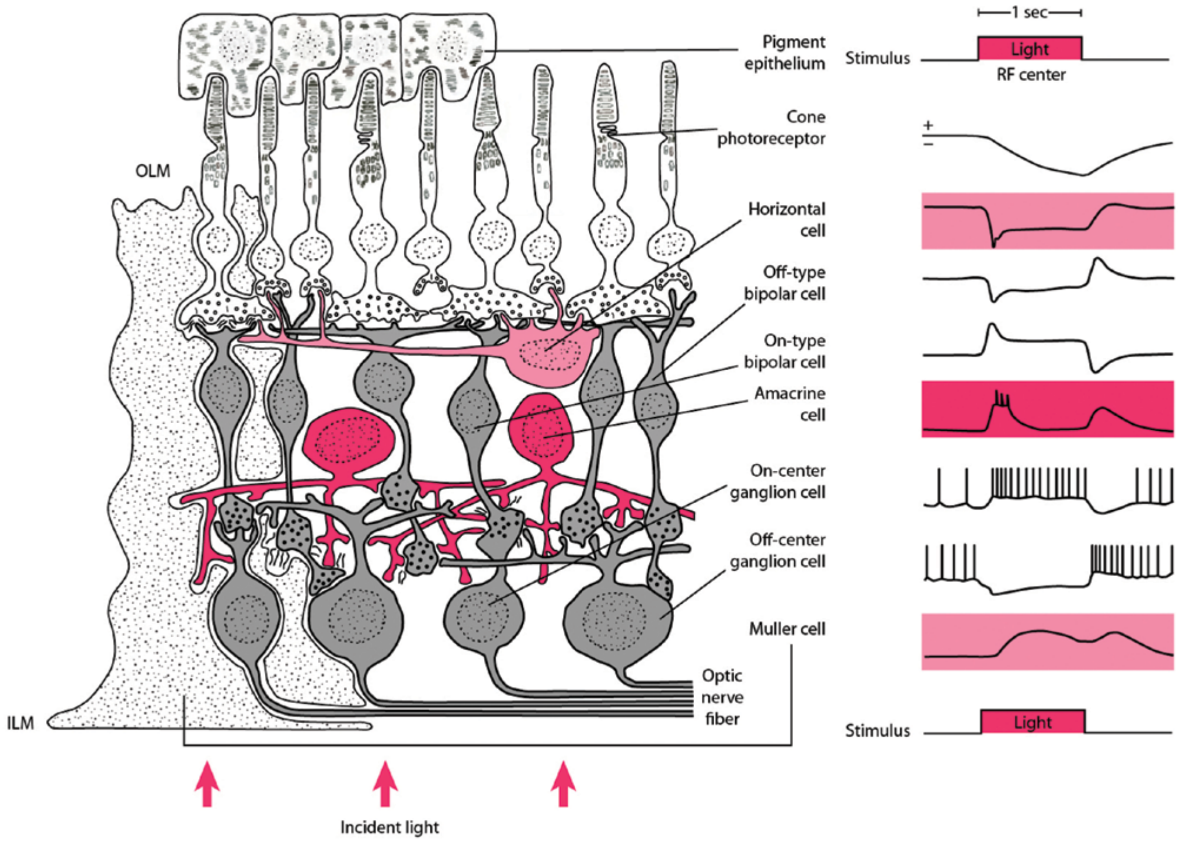



*Figure 3.34 Light –induced electrical activity of different retinal cells: receptors, bipolar cells, horizontal cells, amacrine cells, ganglion cells.*

A ganglion cell generates a nerve impulse that is further transferred to the brain via the visual nerve. The strength of the response of a ganglion cell is encoded by the firing rate of the impulses it generates. Due to the branched structure of the neural network of the retina, a ganglion cell may respond to signals coming from a considerable number of photoreceptors, which are called the receptive field (RF) of the cell. The RF of a ganglion cell has a specific structure shown in Fig. 3.35. Each RF is arranged into a central disk, the "center", and a concentric ring, the "surround". The center receives signals from neurons and bipolar cells through direct paths, while the surround receives signals through lateral paths, in which horizontal and amacrine cells are extensively involved. A ganglion cell responds oppositely to the stimulation of the center and the surround of its receptive field.

There are two types of retinal ganglion cells: "on-centre" and "off-centre" (see Fig. 3.36). An on-centre ganglion cell responds to the presence of light at the centre of RF and to the absence of light at the surround. An off-centre cell responds to opposite stimuli. The effect of an opposite influence of the RF surround on the RF centre is called lateral inhibition.

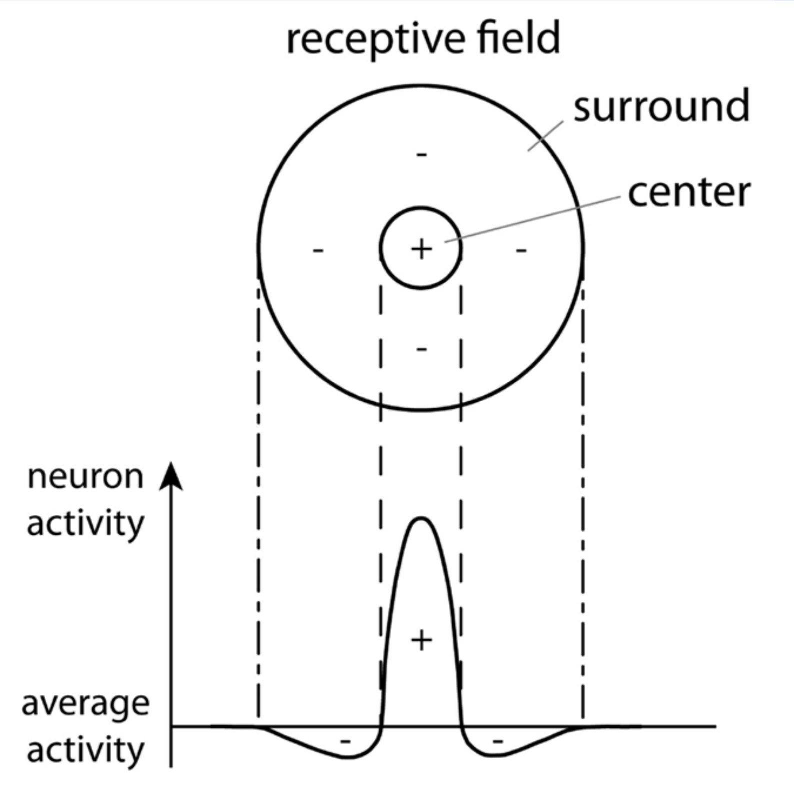



*Figure 3.35 The structure of a ganglion cell above, with a positive responding centre and a negative surround with the receptive field response kernel function shown in the graph below. The convolution product of an input signal with this kernel gives the cell response.*

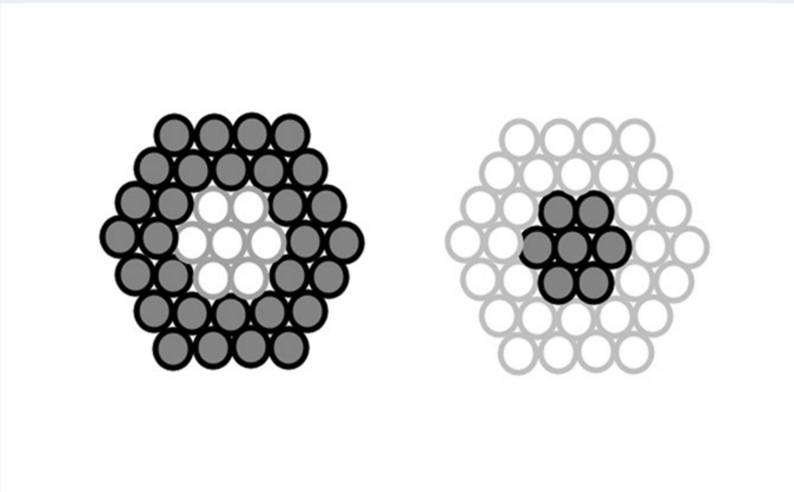


*Figure 3.36 Each circle represents a photoreceptor connected to an on-center ganglion cell (left) or an off-centre ganglion cell (right). Positive response receptors are shown as white and negative as grey.*

Lateral inhibition is an important mechanism that enables perception of object edges and fine details. Its operating principle can be demonstrated by considering the responses of ganglion cells to stimuli of different types (Fig. 3.37). The receptive fields of an on-center (top) and an off-centre cell (bottom) are shown on the left. The corresponding profiles of the impulses generated by the cells are shown on the right. The higher the impulse firing rate, the higher the level of the signal encoded. Consider the operation of an on-centre cell. When there is no light stimulus (just an ambient light to which vision is fully adapted), the cell generates impulses with a low firing rate, which represent a baseline activity for a given ambient illumination. When only the RF centre of the cell receives a light stimulus, the cell generates high-frequency impulses. When the centre and the surround of the receptive field receive similar stimuli, the response of the cell becomes much weaker due to the lateral inhibition. When only the RF surround receives a light stimulus, there are almost no impulses generated.

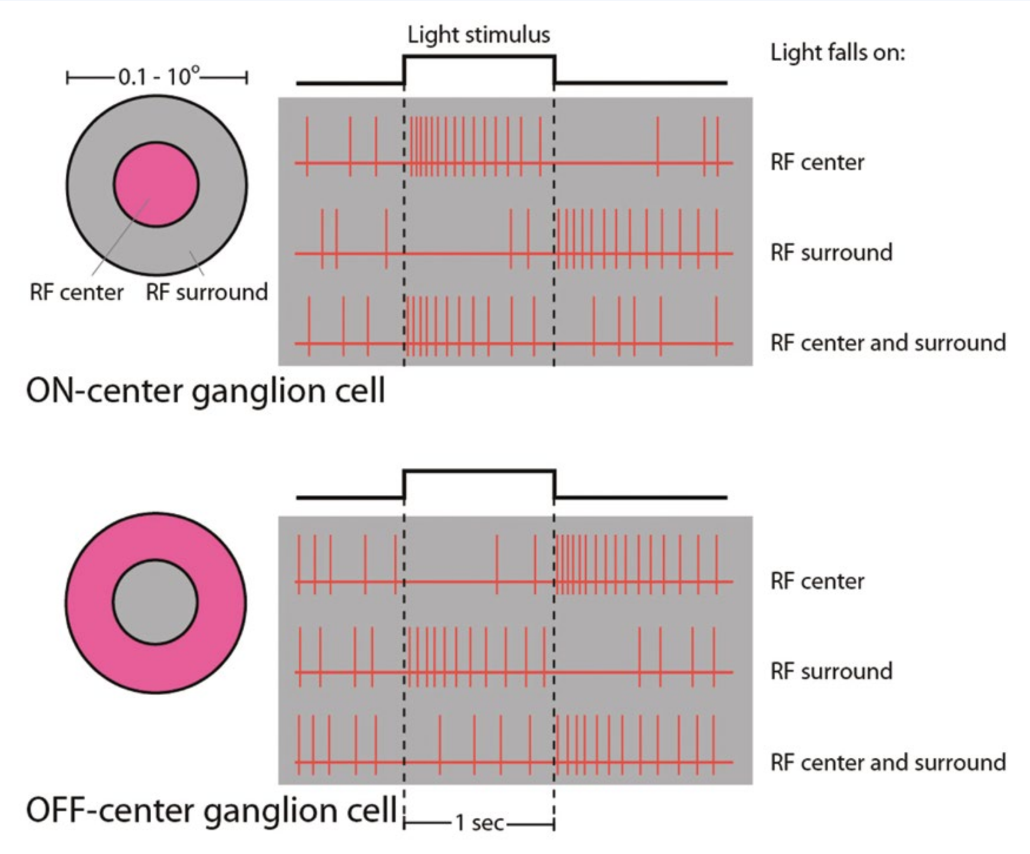



*Figure 3.37 Electrical impulse responses of ganglion cells: on-centre (top) and off-centre (bottom). An on-center cell responds to an emergence of light at the center of a receptive field (RF) and to a vanishing of light at the RF surround. An off-centre cell responds to an emergence of light at the RF surround and to a vanishing of light at the RF center.*

For a stimulus of a constant intensity, the excitation of response impulses is not uniform in time. Right after the appearance of the stimulus, the impulses are generated at a very high firing rate. Then, the rate gradually decreases due to an adaptation process. When the stimulus disappears, the opposite reaction occurs: the impulses stop if the center was stimulated or they start if the stimulus was within the surround. The response of an off-type ganglion cell to a vanishing light stimulus is similar to that of an on-type cell to an emerging stimulus, and vice versa.

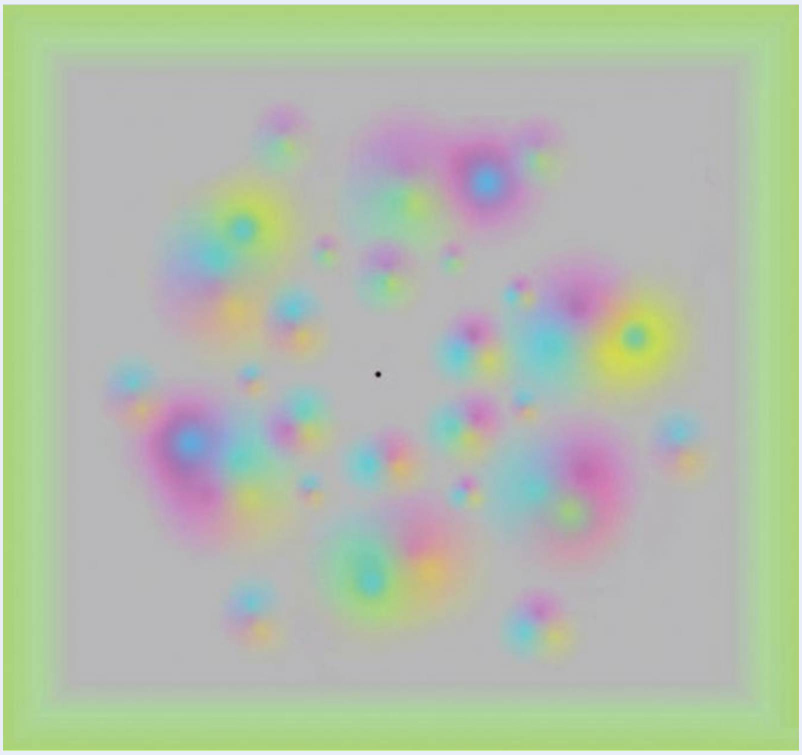


*Figure 3.38 Fix your sight at the black dot. Wait for a few seconds and watch how coloured spots fade away. After the line of sight is changed, the image will be restored. (Source http://www.funxite.com/media/8741-stare-at-the-dot-and.jpg)*

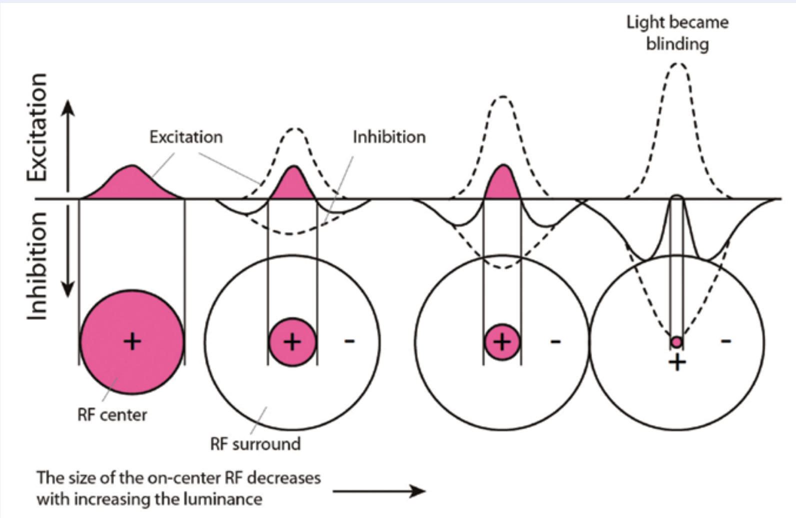



*Figure 3.39 Receptive field and response curve of a ganglion cell (solid line) changes at different levels of adaptation.*

*You can find more details on the psychophysiology of vision, for instance, in (Hubel, 1995).*

An important fact is that the main response of the cells occurs when the stimulus changes, either appearing or disappearing. For example, if you fix your sight on a single point for a few seconds, the perceived image will gradually bleach and finally turn into a uniform field (see Fig. 3.38).

Under well-lit conditions, for example in daylight, the human visual perception system performs a type of colour vision called the photopic vision. Illuminance of more than 3.4 cd/m$^2$ is required for photopic vision to function fully. In dimmer lighting, below 0.034 cd/m$^2$, such as in moonlight, vision becomes monochromatic and is called scotopic. At intermediate levels of illuminance, the mesopic vision system operates.

The spatial resolution of the human eye is limited by two types of factors: optical system effects (diffraction and aberrations) and the ultimate resolution of the sensor (the surface density of retinal receptors and the minimum diameter of the RF centres of the ganglion cells). The best conditions for the optical system are typical photopic conditions, at which the eye pupil size is within the range from 2.5 to 3 mm. In these conditions, the characteristic size of the blur caused by diffraction is about 0.6-1 minute of arc (http://telescope-optics.net/combined_eye_aberrations.htm). This value exceeds the distance between the receptors in the fovea region, which determines the ultimate resolution of the sensor and limits the best visual acuity. When moving from the center of the retina to its periphery, the sensor resolution decreases due to extension of the receptive fields of ganglion cells and, in its turn, starts decreasing the overall spatial resolution.

The resolution also decreases as the illuminance decreases though the vision still stays in photopic mode. This can be explained by reorganization of the receptive fields of the retinal ganglion cells (Fig. 3.39). As a rule, the threshold of RF excitation exceeds that of RF inhibition. However, with increasing illuminance, the corresponding threshold for the lateral inhibition decreases faster. As a result of the superposition of the signals, the size of the on-center RF decreases with increasing illuminance. When the illuminance decreases, the integration area of the receptor signals expands, increasing the light sensitivity and the signal-to-noise ratio.

## 4. ViBox and Diamond Stereo Videos

Accurate evaluation of diamond cut performance requires consistent human observation from many independent experts and consumers. Inconsistency in reviews of the same diamonds can be a result of many factors such as varied illumination, clothing colours worn by observers, distance and motion range, effects of black and white trays, or oils from resting stones between fingers.

ViBox has been designed to address these and related factors to enable observer comparison of diamonds under identical conditions, even when the diamonds or the observers are in different cities, countries or time zones. The comparison process is performed by 'virtualization' by producing high resolution 3D stereo movies in repeatable illumination and environments, with digitally controlled rotational movement of the diamond, which creates the most repeatable and realistic visual perception. Experts or consumers can view and compare diamonds at much higher magnification at the same or different times and locations and argue and debate on any specific cut, clarity, colour and performance attributes. Groups of people can watch and discuss the same movies at the same time. Polls or surveys are easily conducted, and by using this format for sales it becomes possible to do statistical analysis of the diamonds that consumers prefer and purchase when they are comparing two or more videos of diamonds. Viewing realistic 3D movies of diamonds has certain advantages over personal examination.

High dynamic range (HDR) movies can be made with multiple exposures overlaid to display the brilliance and fire of a mounted or a loose diamond. Successive still images of the diamond are taken as the diamond is moved through a defined motion, such as a figure-of-eight and swinging to and fro by a 2 axis gimbal or 360° rotation and swinging back and forward. The camera and the gimbal or stage are controlled by software and hundreds of these images are stitched together to build a movie that can be played with OctoNus stereo viewer or other popular stereo or mono media players or TV's.

A digital full frame Canon camera captures each photo fully controlled by the software that also activates the tilting process of the platform movement between each photo (see Fig. 4.1). The process is fully repeatable with various lighting configurations inside the ceiling of ViBox also selected and turned on or off by the computer. The same observations can be made by observers directly in ViBox with their own eyes rather than with the camera.

A special image splitter (stereo adapter) mounted on the cameras macro lens enables the capture of two sets of images (for right and left eye) in each photo (see Fig. 4.2). Further explanations of the reasons for the use of stereo versus cyclops or monoscopic observation are discussed in detail in Section 3.2. There are samples of stereo movies and links to download the OctoNus Stereo Movie Viewer in the Appendix Data Depository.

### *Application*

Easily operated software controlled lighting environments with various illuminations including white light, warm white light and LED spot lighting create specific and reproducible imaging environments. These include computer controlled camera exposure and aperture settings. Custom white balance and high dynamic range (HDR) tone mapped images ensure a good match with human observation. Videos are exported into modern formats and separate movies can be merged to compare two or more diamonds at the same time. The software enables automatic uploading and sharing of videos with the option to apply independent analysis metrics based on the uploaded video, as mentioned in the map analogy earlier in this article (Section 1), via an online software system.

A 360 degree rotation video format has become a popular way to view inclusions in diamonds because as the stone turns buyers can track and estimate in mono view the actual placement of inclusions and also see if there are surface reaching feathers or gletz. In addition the girdle thickness of most of the stone can be seen.

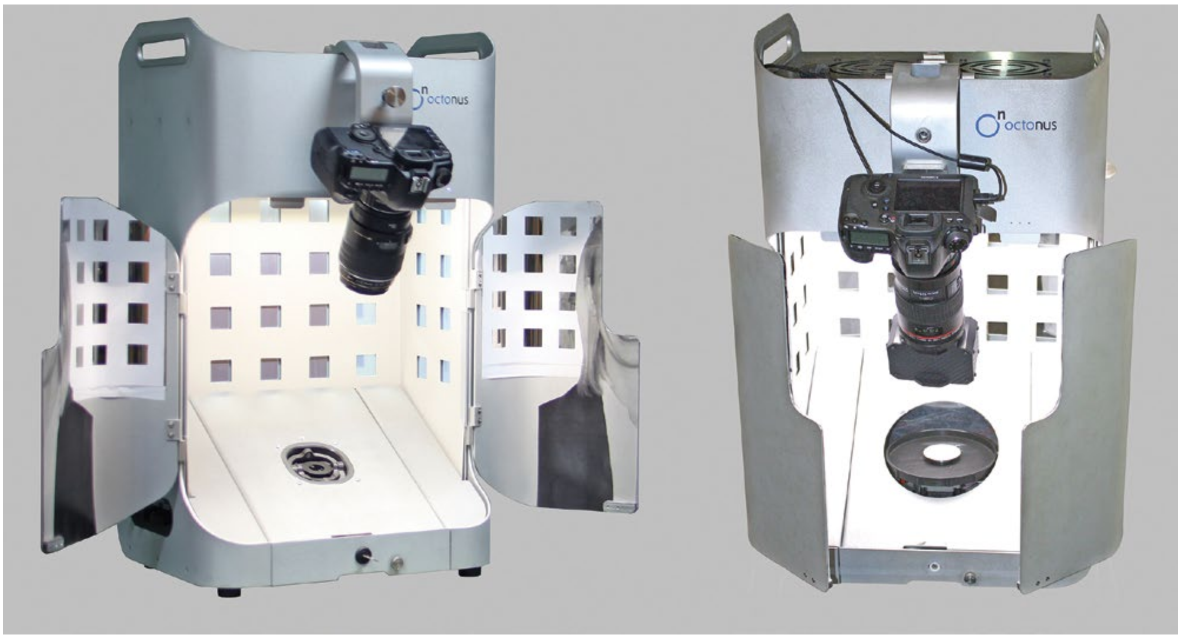



*Figure 4.1 On the left is ViBox with the doors open, the Canon DSLR camera and the figure of eight gimbal for holding diamonds. On the right side the doors are partly closed. The stereo splitter has been added to the camera lens and a 360 degree rotating stage is in place.*

*Figure 4.2 On the left is the custom designed stereo splitter that attaches to the end of the macro camera lens. The image on the right side shows a stereo pair of a diamond captured in ViBox with the OctoNus and Lexus watermark logos.*

A company logo or 'watermark' can be added which will enable, perhaps for the first time, effective branding for diamond manufacturers. The same branded movie can be used to sell a diamond from wholesaler to retailer and to consumer. The authors point out that in almost every other consumer purchase, and especially luxury products, the designers and manufacturer are known and promoted. World over, even the poorest people can name several Swiss watch brands, but very few people, even in developed nations can name one or two diamond manufacturers or diamond brands. We foresee in the diamond industry that some of the best manufacturers will take advantage of this branding opportunity to engage with consumers and learn the distinctions that consumers make between good and bad appearance to produce high quality fancy cuts, and new diamond cuts.

Side by side comparison of two diamonds is an advantage for consumers who are choosing diamonds based on their visual appearance. A user can stop the movie and freeze the diamond image at any time and compare diamonds side by side in high resolution with synchronized positions. Cut quality comparisons can be made by calculating the number of flashes on these synchronized images. A user can play previously recorded movies and compare cuts from old and new movies, including the best Tolkowsky round cuts. No other method allows such detailed, democratic and consistent comparison of different cuts, shapes, and proportions in the same realistic illumination conditions with high repeatability.

ViBox stereo movies can be stored in a database or shared over the Internet allowing many people to view various diamonds in the same conditions. Applications also include education for gemmologists, vendors, salespeople and end consumers. By showing the advantages of better cut quality diamonds, cutters will be encouraged to produce better cuts because buyers have a tool to know the difference.

The Gemological Institute of America (GIA) cut grade has made round diamonds more fungible or easier to trade, at the expense of fancy shaped diamonds that have proven more difficult for laboratories to provide cut gradings. Therefore fancy shaped diamonds are traded at a discount because it takes longer and more effort to sell them. Side-by-side ViBox comparison will help safely and easily select and pair attractive and consistent fancy cut diamonds for experts and novices. A buyer's short list of diamond videos viewed beside a Tolkowsky round 'hearts and arrows' diamond video is a convenient and democratic comparison of overall brightness, size and intensity of fire flashes, scintillation patterns and negative features such as dark zones, all of which become immediately evident.

It is difficult for novice consumers to see clarity differences in diamonds. ViBox magnification, 3D stereo and viewing in motion make it easy to see the smallest inclusion and its position; is it close to the table, under the crown, or lower down near the culet and reflecting? A vendor can show multiple customers the same diamonds and point out salient features. Using the OctoNus viewer, neither diamonds nor observers need be in the same place. Stereo movies can enable buyers to select from large numbers of diamonds, using on-line provided selection criteria, to make fully informed purchasing decisions.

## 5. Discussion & Conclusion

The visual effects described and discussed in Sections 3.1-3.3 show the importance of accounting for properties of human vision when evaluating brilliance, scintillation and fire. We found that the knowledge available concerning human brain function and human perception does not enable taking all these features into account in metrics and to use them to create an automatic and objective diamond beauty evaluation system.

Therefore human vision features should be divided into two important types:

1. Perception features, such as Stevens' law and contrast sensitivity function (CSF), local contrast, etc, confirmed by direct measurements of the human vision system, can and should be taken into account in the creation of computer Performance evaluation metrics.
2. Mathematical models or metrics cannot yet accurately describe important features of vision that enable the creation of phenomena such as optical illusions. But we can and must use knowledge about these phenomena in both the creation of new cuts and subjective evaluation of existing cuts, as well as in developing appropriate consumer language. For instance, we can't 'measure' stereo vision contrast; there are no mathematical tools which can describe the exact contrast value and subjective brightness that emerge in the moment when the observer's eye 'sees' a dark area and the other eye 'sees' a light area, or different eyes 'see' different colours in the same area. But from the study of existing scientific literature and from our tests we know which factors

play a role in creating contrast. So for any particular cut we can check each facet in order to measure the probability of stereo contrast emerging; for example as a result of a non-symmetrical observer's head and body obscuration of light sources. We can evaluate the number of the facets that have a high probability of this contrast emerging and evaluate their distribution in a diamond. If there are very few such facets, or if they are distributed in one small area of the diamond only, we can conclude that diamond cut will not gain the full benefit of creating contrast and high subjective brightness, and thus cannot belong in the class of High Performance cuts.

At present the overall evaluation of diamond beauty and subjective factors contributing to diamond beauty can only be performed by expert observation. In order to improve observer consistency, ideally metric algorithms would check that evaluations are consistent with the evaluation of other gems which have close characteristics to the one being examined. These characteristics should be individual performance features that can be assessed objectively because objective metrics, such as those we introduced at the IDCC1 in 2004 [see Proceedings, reference 64], enable comparison of different cuts and shapes to each other. These metrics will be described in a future article. Objective metrics can be the fundamental base to enable the grading of different cuts in one system with good agreement with human perception. Objective metrics do not evaluate a diamond's beauty; they evaluate how close two diamonds are to each other for each individual feature of optical performance.

In our opinion, diamond evaluation and new cut development should be based on complementary dual application of objective metrics and subjective evaluation. The attempts to oppose the use of either of these two methods will result in a deadlock.

If the diamond industry continues to use only subjective methods of cut evaluation, then the development of new high Performance cuts will be held back and confidence between vendors and consumers will remain low. The usage of objective systems alone will often result in contradictions between human evaluation and a system rating, leading again to low confidence in the system. The combination of subjective evaluation and objective methods will enable the development of high Performance cuts and establish a sound dialogue with consumers based on well-reasoned evaluations.

At a first glance this combination may appear either impossible or weird. But further consideration finds a vast number of successful examples of how this works in human culture. Two examples are mentioned below:

When a chef writes a recipe the objective part defines the measures of the ingredients to be used, cooking times and methods. But you can probably judge who cooked from the recipe: a chef or a trainee, because the subjective way of interpreting a recipe can make a big difference. The authors, for example, try to avoid favourite restaurants on the Chef's day off.

Two musicians can play from the same objective notation, but your preference depends on their subjective interpretation. The whole impression from music is a combination of objective base (notation) and subjective approach (musician's style).

As in the analogy used in the development of maps, there is great value in many independent observations made with the same system and environment. A system is required that enables evaluation with high repeatability and consistency with other diamond observations despite the low accuracy and repeatability of one subjective measurement (colour, clarity, contrast, brilliance). Such a system would be close to objective in its consistency and it would be trustworthy due to reduced contradictory results.

In subsequent articles on the technologies of methods of Performance evaluation we will discuss the application of information we have learned during research on human perception published in this article.

For example the light box we created called ViBox enables diamond observations to be performed by different people with the same system, and the observations can be recorded and documented. A large number of independent observations are required to create a cut 'map'. ViBox photo documentation technology and stereo movies enable the creation of algorithms of automatic diamond flash calculation and analysis. This will be valuable when also considering human vision properties.

There is a key question, which is better – one big flash or two small ones? The answer is difficult and not obvious even if all three flashes have the same brightness, colour, duration and if the sum of two flashes is the same as the area of the one big flash. Taking Performance evaluation into account requires this question to be answered, along with accounting for difference in size, location, brightness, colour and duration of these flashes. The problem seems at first glance, to be insoluble in the near future.

When we find two diamonds which have close metrics: size, brightness, flashes etc, and if experts evaluate the Performance of these two diamonds as the same, then it validates the system. But if the two diamonds with similar metrics and the Performance of this pair of diamonds were scored differently by experts, then it means that the system does not take into account some critical aspect of human perception. If two diamonds have close flash statistics, but different expert evaluation, this will mean incorrect counting of some important factor of flash statistics, or expert error. Having such statistics for at least 5-10% of diamonds sold annually will make it possible, within several years, to have data (a map) for totally automatic Performance evaluation for 99% of diamonds. This is because for gems with similar flash statistics prior evaluations can be used, while for 1% of gems with new and unique statistics such as totally new cut phenomena (or new 'DNA'), expert evaluation would be used. Expert evaluations should be constantly verified by Crowdsourcing methods based on consumer evaluations. We are planning to discuss these subjects in the third article. In the next, second article, we will discuss how we use metrics based on 3D cut models and special illumination models for rapid new High Performance cut development by means of automatically rejecting cuts with low optical metric values, and expert evaluation of cuts with high metric values based on stereo movies created with DiamCalc software (see DiamCalc webpage link in the Reference section).

To see demonstrations of phenomena described in this article we invite readers to visit the data in the depositary web-site. To view stereo photos and to play stereo movies we recommend NVIDIA 3D Vision compatible computers. (http://www.nvidia.com/object/3d-vision-system-requirements.html). PC's with NVidia GeForce 200 or a more recent video adapter is recommended (and for window stereo view — NVIDIA Quadro 2000 or more recent). It is important to make sure that the monitor supports NVIDIA Light Boost and NVidia 3D Vision 2 glasses are used. Examples of compatible monitors are ASUS VG278H and VG278HE. OctoNus Stereo Viewer application is recommended to play stereo movies. The download and instruction for its use is also published in the depository.

Readers may also watch stereo movies using 3D TV's or other 3D monitors. We hope that while watching these stereo diamond movies, readers will discover many additional interesting phenomena, as this article does not cover them all. We invite readers to send feedback to: cut@octonus.com

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## Appendix

The link below contains 3D diamond files, ViBox movies, Stereo tests, Illusions and additional material referred to throughout this article.

www.Cutvision.com/stereo