# Binocular Brightness Combination: A Mechanism for Combining Two Sources of Rather Similar Information*

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Our perception of the world is strongly restricted by the properties of our senses. These provide us with a rather selective view of the world where much of the potentially available information is not directly accessible. But what is accessible has been proven to be sufficient for survival, at least until now. The Ptolemaic view of the world is a nice demonstration of what is accessible by direct and unaided perception: Even if we know that the stars' distances to the earth vary greatly they all appear to be fixed to the sky at the same distance. We are not able to discriminate their distances. So unaided perception gives us a distorted or even wrong view of the world. Nevertheless, although this is hard to quantify, it seems reasonable to say that most of our direct view of the world is correct.

For ordinary people this is an obvious fact. So obvious that for example it needs some really good arguments to convince new students that while perceiving generally is easy and almost effortless, studying perception and explaining perceptual phenomena is very hard. This, by the way, is a striking difference to other cognitive behavior: Playing chess for example is hard for most of us but machines have been built which do it much better than most of us will ever be able to do it. On the contrary, perceiving is easy for all of us but there is no machine which does it nearly as good as any of us.

One of the major problems with perception is that the information which is available for our senses contains a lot of noise. If we ask what is important for orientation in the world we have to concede that much of the important and accessible information is contaminated by less important information. And often information about different facts is confounded and cannot be extracted by simple means. Think about brightness or lightness perception. The light arriv-

*This paper was written while the author stayed at the Center for Interdisciplinary Research of the University of Bielefeld.

ing in our eyes from object surfaces depends both on the reflectance properties of the surfaces and on the illumination. To recognize objects there should be a mechanism which gives us reflectance properties of the objects which are independent of illumination. However, the perceptual system should better not throw away the illumination information completely, since then it might be difficult to estimate the time of sunset which could be dangerous in a natural environment.

Problems like this are treated under the label of constancy or invariance properties of perception. These usually deal with situations where some perceptual attribute of a stimulus is invariant under certain transformations of the stimulus. A typical example is the above mentioned notion of lightness constancy under varying illumination conditions.

Lightness or perceived surface color constancy are examples for invariance properties under stimulus changes which are independent of the observer. Additional complications for the perceiving organism are created by the fact that most active behavior of the organism itself also results in certain variations of the visual stimulus. A typical example is in motion perception. Motion of the outside world and self motion of the organism are confounded in the retinal image. If the retinal image is to be used as a source of information about object motion then this confounding has to be resolved.

Before reporting an empirical analysis of some invariance properties, let me point to one common result in almost all experimental studies of constancy phenomena. All of these are invariance properties against some action or transformation in the stimulus situation. The result of the invariances are that some perceived attributes of the stimuli are constant under the respective transformation. However, I know of no case where this invariance or constancy is perfect. Very often research has concentrated on the attribute which remains nearly invariant and this usually has some obvious survival value. However, in most cases it also seems useful not to have perfect invariance. Since having perfect invariance means that the respective stimulus transformation goes unnoticed. And in most cases this would be a severe disadvantage.

The experiments to be reported here deal with binocular combination of brightness. Usually the two retinal images are rather similar. This is especially true for fused regions of the visual field and with respect to the distribution of color. For this situation one would expect that each monocular component contributes equally to the fused image. One also would expect that the brightness of a fused region of the visual field, called “binocular brightness”, shows a strictly monotone dependence on the monocular stimulus intensities in this case. This is empirically confirmed.

However, the situation becomes different if the monocular stimulus components become rather different in intensity or contrast. An extreme case is the closure of one eye. We hardly notice any change in color appearance or in brightness if one eye is closed as compared to binocular viewing. Thus the mechanism for combining the two sources of visual information works such that both components are weighted equally when the stimuli are almost equal and is dominated by a single source when this source dominates the stimulus.

The first person who investigated this problem experimentally was G. Th. Fechner in 1861 (Fechner, 1861). He looked at the sky while one of his eyes was covered with a gray filter. So he could estimate the brightness of the sky for binocular viewing with one eye observing freely and the other eye getting varying amounts of light. He mostly made judgements about the change of perceived binocular brightness when closing the eye with the filter in front as compared to observation with both eyes. He found a psychophysical function which showed two special properties (Fig. 1):

1. The function is not monotone increasing. For zero filter transmittance the brightness corresponds to monocular viewing. Increasing the filter transmittance from zero upward first leads to a decrease in binocular brightness until a minimum is reached and only then the brightness is increasing with increasing transmittance of the filter.

2. For binocular viewing without filter the brightness is approximately equal to monocular viewing, with some small advantage of binocular viewing.

The question then is how a model of the binocular fusion mechanism might look like. Its general structure should contain a monocular input transformation $f(x)$ and some binocular combination rule $F(x, y)$:

$$B(x, a) = F[f(x), f(a)].$$

Questions like these are traditionally treated by goodness of fit methods. I will use a different method here which may be viewed as an experimental method to analyze the form of the psychophysical function involved. This will allow me to experimentally test not only single models but even larger classes of models with common structural properties.

In the experiment the subject has to compare pairs of dichoptic stimuli. Each of these contains stimulus intensity components $x$, $y$, for the left and stimulus intensity components $a$, $b$ for the right eye. The stimuli are presented such that both the components $x$ and $a$, and the components $y$ and $b$ are fused, such that we can ask the subject to compare the brightness of $(x, a)$ and $(y, b)$. We

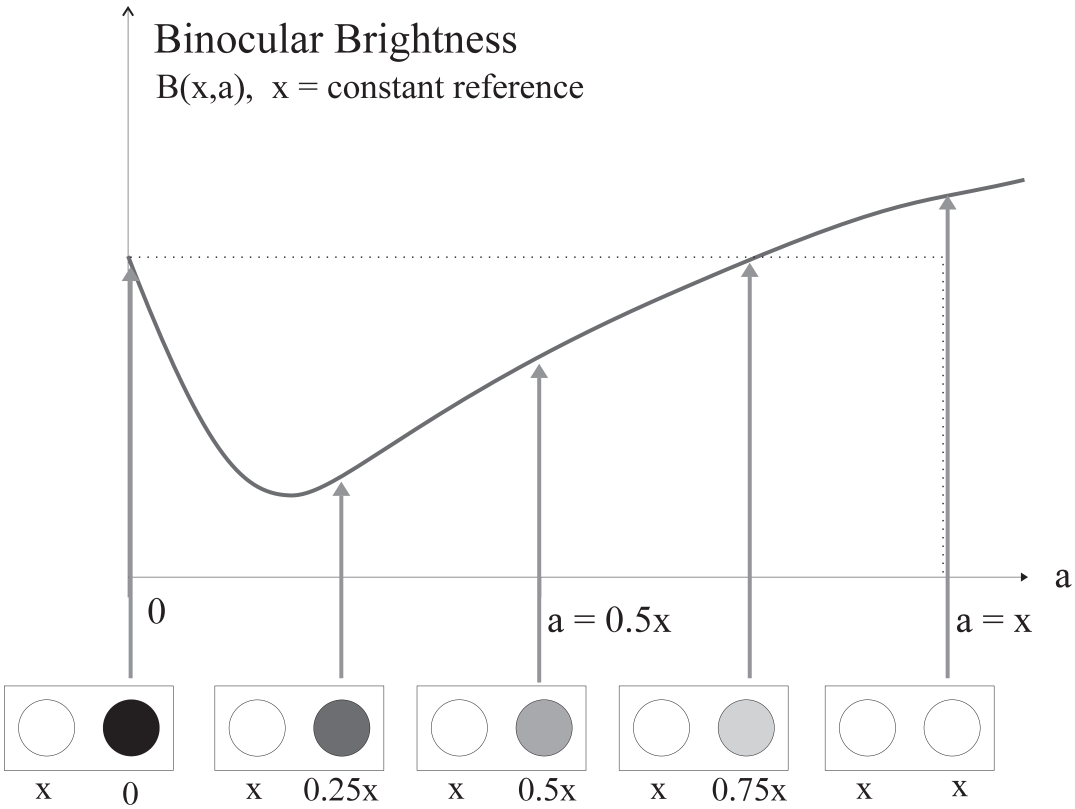


FIGURE 1. Fechner's psychophysical function shows binocular brightness $B(x, a)$ for constant values of $x$ and increasing filter transmittances $a$. Note that there is an initial decrease of binocular brightness when changing from monocular viewing to binocular viewing with one eye covered by a low transmittance filter. Monocular and binocular observation of the same stimulus results in almost the same brightness: $B(x, 0) \sim B(x, x)$.

write $(x, a) \succsim (y, b)$ iff the subjects judges $(x, a)$ to be at least as bright as $(y, b)$. In order to analyze the structural properties of binocular fusion we can then ask what happens if we change the intensities of the stimuli involved. To derive some hypotheses about the behavior of the psychophysical function for binocular brightness we look at the following condition of *intensitiy invariance*: if $(x, a) \succsim (y, b)$ then $(tx, ta) \succsim (ty, tb)$ for all real numbers $0 < t < \infty$, where $tx$ is the intensity $x$ multiplied by the factor $t$. Fechner describes a condition which may be interpreted as intensity invariance: "... daß die Helligkeit des Himmels von keinem wesentlichen Einfluß auf die Lage des Indifferenzpunctes ist" (Fechner, 1861, p. 422).

With this condition in mind we can now look at specific points of the psychophysical function in Fig. 1. The *equivalence point* $e(x)$ of a psychophysical function for binocular brightness is defined by $(e(x), 0) \sim (x, x)$. It is that stimulus $e(x)$ which, when viewed monocularly, looks equal to $x$ viewed binocularly; and the *minimal point* $m(x)$ is that stimulus which, when combined with $x$, results in the lowest possible brightness: $(x, m(x)) \succsim (x, a)$ for all $a$. If we combine these definitions with the intensity invariance condition we get the following two functional equations for $e(x)$ and $m(x)$:

$$\begin{aligned} e(tx) &= t\, e(x), \\ m(tx) &= t\, m(x). \end{aligned}$$

The solutions to these functional equations are unique and rather simple (Aczél, 1966). Both functions $e(x)$ and $m(x)$ have to be linear functions of the reference intensity:

$$\begin{aligned} e(tx) &= \beta\, e(x), \\ m(tx) &= \gamma\, m(x) \end{aligned}$$

for some non-negative real valued $\beta$ and $\gamma$. The equivalence point and the minimum point thus have to move upwards in a linear fashion for increasing reference intensities (Irtel, 1991).

The previously derived behavior of the equivalence and the minimum point describe characteristic points of the psychophysical function for binocular brightness. They capture the non-monotone behavior of this function and thus actually describe their most interesting points, namely those points which are most different to the usual psychophysical functions found in psychology. These points also are those points which should be investigated experimentally. This is usually not done if data are collected for fitting some equation to them. An example are the data collected by de Weert & Levelt (1974). A closer look at their data set shows that they actually looked at a set of psychophysical functions at various levels of intensity for the reference stimulus. However, in their data the minimum point is constant at 10 cd/m$^2$ simply because they did not collect any other data between 0 and 20 cd/m$^2$. Such a set of data actually is not very useful for testing any model of binocular brightness fusion because the most critical part of the binocular brightness function is not tested empirically. De Weert and Levelt's model does have the intensitiy invariance condition formulated above as a necessary consequence.

Since none of the published sets of data on binocular brightness combination allows for testing the intensity invariance condition an experiment was run to explicitly test how the equivalence point and the minimum point change under varying reference intensity levels.

## Methods

The experimental setup is described in full detail by Irtel (1991). It was run on a precisely calibrated monitor (BARCO CDCT 51/3) controlled by a PC with a Matrox PIP 1024 graphics controller board providing for 8 bit resolution or 256 steps per color channel. Calibration was done by an LMT 1000 photometer with high accuracy $V(\lambda)$ sensitivity function. The subject viewed the screen through a mirror haploscope such that the left part of the screen was visible for the left and the right part of the screen for the right eye only. A chinrest was used for head fixation. The display and the haploscope were adjusted for optimal fusion of the dichoptic stimuli.

The display background was black and during adaptation there was a bright 120 cd/m$^2$ ellipsoid adaptation field extending 6° vertically and 4° horizontally with a small dark fixation mark. The stimuli were bright half disks of 0.5° radius on a dark background positioned above and below the fixation mark with a 0.5° gap between the upper and the lower dichoptic stimulus. Each of the two dichoptic stimuli had a left eye and a right eye component which were fused and appeared as a single half disk for the subject. Stimulus display duration was 1.2 s and there was an adaptation period of 6 s between trials. The task was to compare the upper and the lower half disk with respect to brightness.

The first part of the experiment was used to find that stimulus component $e(x)$ which, when presented together with a zero right eye component, appeared equal to the stimulus $(x, x)$. $x$ was set to 3, 6, 12, 24, 48 and 96 cd/m$^2$. The value of $e(x)$ was found by an adaptive 1-up-1-down procedure limited to 20 trials. Starting values were optimized according to preliminary data. Results were computed from the turning points only. The second part of the experiment was used to find the minimum points $m(x)$ for each of the above listed reference values $x$ between 3 and 96 cd/m$^2$. This was done by presenting stimuli of the form $(x, y)$ and $(x, y+\delta)$, where $\delta$ was a small luminance increment. An adaptive procedure was set up such that $y$ was increased whenever $(x, y)$ was chosen to be brighter than $(x, y+\delta)$ and vice versa. The increment $\delta$ was chosen according to preliminary data. The adaptive procedures were stopped after 8 turning points and the results were computed from these.

## Results

The results for $e(x)$ and $m(x)$ are shown in Fig. 2 and 3. Figure 2 shows results of a comparison of stimuli of the form $(x, x)$ and $(y, 0)$ where the first component is presented to the left and the second component is presented to the right eye only. It is clear that for all intensities the single component stimulus $(y, 0)$ needs a little more intensity than the two component stimulus $(x, x)$. In general the factor is around 1.2 such that monocular stimuli need about 20 % more intensity in order to appear equal in brightness to binocular stimuli.

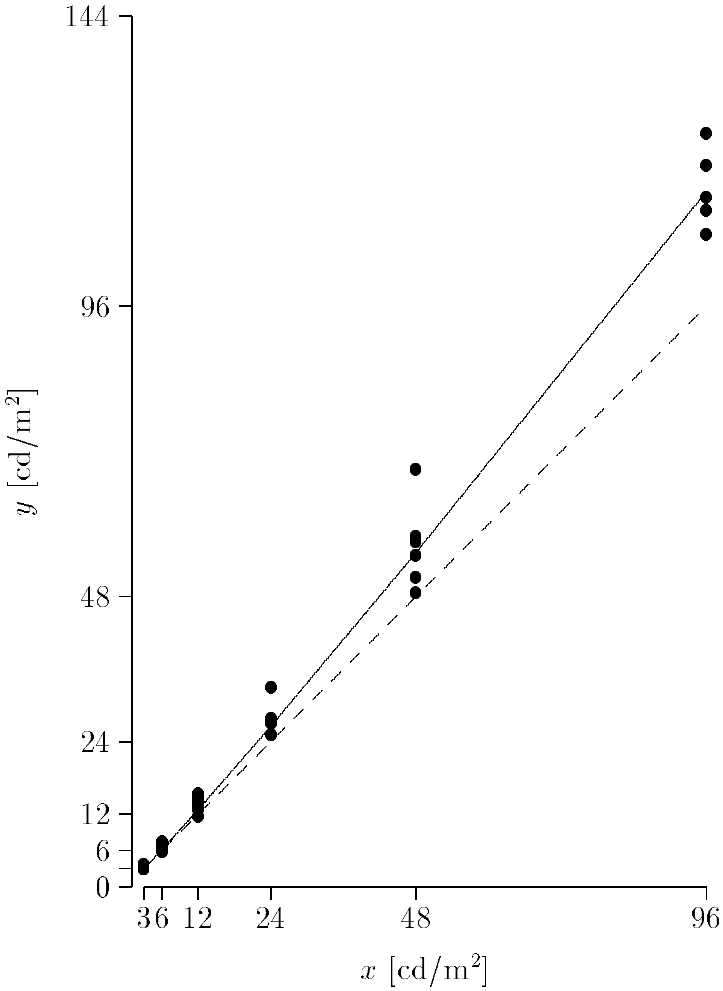


FIGURE 2. Comparison of dichoptic stimuli of the form $(x, x)$ which have the same binocular brightness as stimuli of the form $(y, 0)$. The data are from 3 subjects with 2 measurements for each value of $x$ (one data point at $x = 96$ cd/m$^2$ is missing). The dashed line represents $y = x$. There is an almost constant binocular advantage of 20%. The solid line shows the predictions of the model.

The results for the minimal point are shown in Fig. 3. Intensity invariance requires that the minimum points increase linear with reference intensity. This clearly is not the case. The values of $m(x)$ increase much slower as expected.

## Discussion

Although the data of Fig. 2 for the equivalence points indicate a linear relation between monocularly and binocularly viewed stimuli of equal binocular bright-

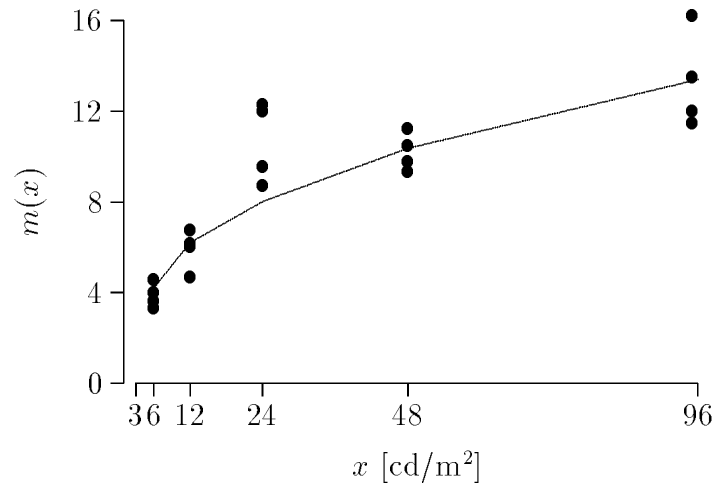


FIGURE 3. Minimal stimuli $m(x)$ as they depend on the reference intensity $x$. Intensity invariance requires that $m(x)$ is linear in $x$. Clearly the data of 4 subjects show a strong deviation of linearity. The solid line represents predictions of the model.

ness, the results in Fig. 3 clearly refute intensity invariance. The minimum point of the psychophysical function for binocular brightness grows much slower than would be expected from intensity invariance. This refutes all models of binocular brightness which allow for a separation between the intensity dependent factor $t$ and the fusional process $B(x, a)$:

$$B(tx, ta) = G_t[B(x, a)].$$

Thus the fusion process $B(x, a)$ itself depends on the intensity factor $t$. This actually rejects almost all models of binocular brightness combination which have been suggested, including that of de Weert and Levelt (1974) and that of Curtis and Rule (1978). Both have intensitiy invariance as a necessary condition. The major reason for these models to fail is that they assume a power function as a monocular input transformation. Note that power functions are intensity invariant: For $f(x) = x^\alpha$ we get $f(tx) = t^\alpha f(x)$ and thus the effect of $t$ can be separated from the function itself, we have $f(tx) = G_t[f(x)]$. This also holds for a reasonable choice of binocular fusion functions $F(x, y)$ (Aczél, 1966).

An input transformation which does not have this property is the logarithmic function. MacLeod (1972) has already suggested to use this function as an input transformation for binocular brightness. A model for binocular fusion of color has been suggested by Schrödinger (1926) and both de Weert and Levelt's (1974) and MacLeod's (1972) models are derived from it. He suggested that each monocular component has to be weighted by a function which gives the relative intensity of each input signal. Thus Schrödinger's weight function is

$$w(x, a) = \frac{f(x)}{f(x) + f(a)},$$

where $f(x)$ is the monocular input. Note, however, that using this weight function alone is also ruled out by our data since it suggests that $w(x, 0) = 2\, w(x, x)$ and thus binocular and monocular observation of the same stimulus should result in the same brightness. We thus suggest a model with the following properties:

1. The monocular input transformation is a logarithmic function with an adaptation dependent threshold parameter $x_0$.
2. Binocular fusion is a mixture of monocular inputs with weights that depend on relative signal strengths as suggested by Schrödinger (1926).
3. The intensity dependent weights have a compression parameter $k$, such that they do not add up to 1. If this parameter is less than 1 then there is a slight advantage for dichoptic stimuli with similar intensities as compared to stimuli with strongly different intensities in both eyes.
4. There also is an eye dominance factor $\delta$ for giving different weights to the stimuli in the two eyes.

We thus have the following model:

$$
\begin{aligned}
f(x) &= \begin{cases} \phi_0 + \log(x/x_0) & \text{if } x > x_0, \\ \phi_0 & \text{if } x \leq x_0. \end{cases} \\
w(x, a) &= \frac{f(x)}{f(x) + f(a)} \\
B(x, a) &= \delta\, w(x, a)^k\, f(x) \;+\; \frac{1}{\delta}\, [1 - w(x, a)]^k\, f(a)
\end{aligned}
$$

Here $x_0$ is the adaptation dependent threshold parameter. Its value has been found to be between 0.03 and 12.0 cd/m$^2$, depending on adaptation stimulus level. $k$ determines the binocular advantage for equal components in both eyes, its value is around $k = 0.92$, and $\delta$ describes individual eye dominance and should be constant for a single subject.

The solid lines in Figures 2 and 3 show the predictions of the model for the data of the experiment. The parameter $\delta$ was set equal to 1 for these data since no comparison was possible between the two eyes in this experiment. Using the data of all subjects and all tasks $k$ was estimated as $k = 0.919$ and $x_0$ was estimated as $x_0 = 4.2$ cd/m$^2$ by least squares minimization. Figure 4 contains a comparison of the data and the model's prediction for an experiment published by Irtel (1986). The major difference to the present study was that subjects were dark adapted in this case. This results in an estimate of $x_0 = 0.39$ cd/m$^2$ for the threshold value while $k$ stays almost constant at $k = 0.925$.

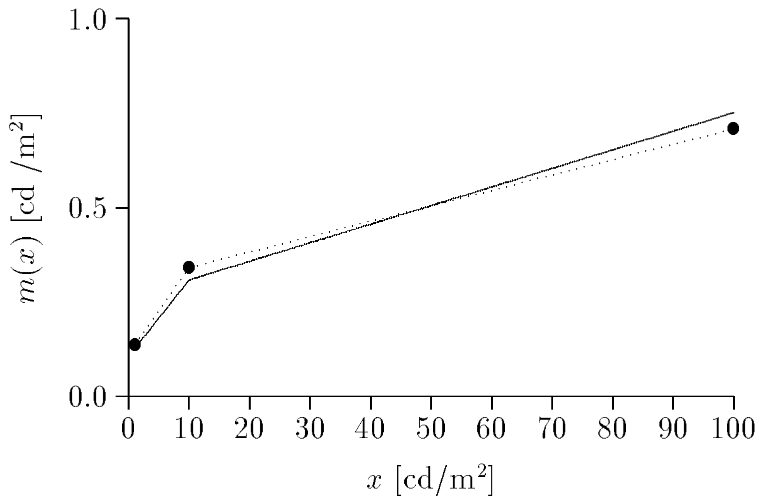


FIGURE 4. Minimal stimuli from an experiment where the subject was dark-adapted (Irtel, 1986). Increase of minimal stimuli also is not linear. Data are connected by dotted lines, predicted points are connected by solid lines. Parameter estimation for the model results in $x_0 = 0.034$ and $k = 0.95$.

Fechner had called his experiment "Paradoxer Versuch" because it showed that a stimulus can look brighter even if less light enters the eyes. In my view the non-monotone psychophysical function is a consequence of two simple invariance properties:

1. Monocular and binocular viewing results in almost the same brightness.

2. For fused dichoptic stimuli with rather similar components there is a monotone relation between stimulus luminance or contrast and brightness.

As a consequence of these two conditions one gets the non-monotone psychophysical function of binocular brightness. The function in Fig. 1 has to have approximately the same ordinate value $B(x, a)$ for $a = 0$ and for $a = x$ and it has to be monotone increasing at $a = x$. This implies that there is a local minimum between $a = 0$ and $a = x$.

Thus it seems that a major reason for Fechner's paradox is our ability to independently close each single eye. Since the mechanism described ensures that the world's brightness does not change significantly if we close one of the two eyes. If this is true then, contrary to the claim of Lehky (1983), we should not have a similar non-monotone effect in binaural loudness combination, since there is no need for it there. Hübner (1991) looked for Fechner's paradox in binaural loudness combination, but could not find it. This supports the idea that Fechner's paradox is a result of approximate binocular brightness constancy under change of viewing condition.

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