Evaluation of Image-Based Contrast Metrics for Predicting Perceived Transparency

Bachelor Thesis

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I hereby declare that the thesis submitted is my own, unaided work, completed without any unpermitted external help. Only the sources and resources listed were used.

Berlin, 27.03.2023

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Abstract

In visual perception research, it is known that the perceived transparency of a medium depends not only on its physical transmittance, but also on its luminance and the background where it is placed. Previous work by Robilotto and Zaidi (2004) showed that perceived transparency increases with increasing background contrast. In contrast, Chubb, Sperling, and Solomon (1989) suggested that it increases with decreasing background contrast. In my thesis, I examined this problem and studied the effect of background contrast on the perceived transparency of the transparent media. Stimuli were variegated checkerboards with a transparent medium in front of it that covered the background partially. I varied the transmittance α and luminance of the medium on two backgrounds, with the highest and lowest contrast. Then the transparent media were cut and pasted on backgrounds with various contrast. I judged the transparency with my subjective inspection. I also calculated the contrast with different contrast metrics: *MC*, *SAM*, *SAMLG*, and *SAW*. Moreover, I measured the ratio between the contrast of the transparent medium and the background for every stimulus with different metrics as well as the difference between the ratios of the two compared stimuli. I examined whether the ratio can be considered as perceived transparency and whether the difference between the ratio can be interpreted as the difference in perceived transparency. I observed that for the most of the stimuli, the stimuli with lower background contrast is perceived more transparent then the stimuli it is compared to. Additionally, there was a relation between the ratio and the perceived transparency only when the medium seem transparent and the contrast metric *SAMLG* can predict the difference of perceived transparency better than other three contrast metrics.

Zusammenfassung

Aus der visuellen Wahrnehmungsforschung ist bekannt, dass die wahrgenommene Transparenz eines Mediums nicht nur von seiner physikalischen Durchlässigkeit abhängt, sondern auch von seiner Leuchtdichte und dem Hintergrund, auf dem es platziert ist. Frühere Werke von Robilotto and Zaidi (2004) zeigten, dass die wahrgenommene Transparenz mit zunehmendem Hintergrundkontrast zunimmt. Im Gegensatz dazu schlug Chubb et al. (1989) vor, dass es mit abnehmendem Hintergrundkontrast zunimmt. In meiner Bachelorarbeit bin ich diesem Problem nachgegangen und habe die Auswirkung des Hintergrundkontrasts auf die wahrgenommene Transparenz der transparenten Medien untersucht. Reize waren Schachbrettmuster mit einem transparenten Medium davor, das den Hintergrund teilweise bedeckte. Ich habe die physikalische Durchlässigkeit α und die Leuchtdichte t des Mediums auf zwei Hintergründen variiert, mit dem höchsten und dem niedrigsten Kontrast. Dann wurden die transparenten Medien ausgeschnitten und auf Hintergründe mit verschiedenen Kontrasten geklebt. Ich habe die Transparenz mit meiner subjektiven Inspektion beurteilt. Ich habe den Kontrast mit verschiedenen Kontrastmetriken berechnet: *MC*, *SAM*, *SAMLG* und *SAW*. Außerdem habe ich das Verhältnis (Ratio) zwischen dem Kontrast des transparenten Mediums und dem Hintergrundkontrast für jeden Stimulus mit unterschiedlichen Metriken, sowie die Differenz zwischen den Verhältnissen der beiden verglichenen Stimuli gemessen. Ich habe untersucht, ob das Verhältnis als wahrgenommene Transparenz angesehen werden kann und ob die Differenz zwischen den Verhältnissen als Unterschied in der wahrgenommenen Transparenz interpretiert werden kann. Ich habe beobachtet, dass bei den meisten Stimuli die Stimuli mit geringerem Hintergrundkontrast transparenter wahrgenommen werden als die Stimuli, mit denen sie verglichen werden. Außerdem gab es nur dann einen Zusammenhang zwischen dem Verhältnis und der wahrgenommenen Transparenz, wenn das Medium transparent erscheint und die Kontrastmetrik *SAMLG* den Unterschied der wahrgenommenen Transparenz besser vorhersagen kann als die anderen drei Kontrastmetriken.

Acknowledgement

I would like to thank my supervisor Dr. Guillermo Aguilar for his time, patience, and guidance. His encouragement and advice at every step helped me write the thesis.

Contents

1 Introduction

Every day we see through transparent media. A transparent medium can be smoke, glass, or foggy air. The objects and surfaces are in a three-dimensional environment in the visual world, which is not the case in the human visual system as the inputs to human visual systems are two-dimensional arrays of light intensities, not three-dimensional objects. These inputs depend on many variables, such as the reflectance of the surface, the light intensity, and other characteristics of the background (Singh & Anderson, 2002). Therefore, the perceived image projected in the retina of a surface can depend on its physical conditions, and two identical surfaces can be perceived differently.

1.1 Human Visual System

The human visual system is able to distinguish two different layers in the same retinal area. When there is a medium with a transmittance in front of a background, the human visual system recognizes two surfaces: the background and the transparent medium in front of it. Figure 1 shows the process of image formation. As can be seen, the retinal stimulus is generated by the transmission of the light (transmittance) by the illumination (luminance) source on the reflectance. The perception of a stimulus depends on three factors: luminance, reflectance, and transmittance. There are many combinations of these physical factors that can be perceived the same as the same retinal stimulus is generated, although the physical characteristics of the stimuli are different (Purves, Wojtach, & Lotto, 2011). Now assume that the illumination is fixed. Then, the retinal stimulus, which is the perceived transparency, is a function of the reflectance of the surface and the transmittance between the surface and the human eye. It is observed that perceived transparency varies with different reflectance, even if the physical transparencies are identical. The perceived transparency of a medium is not only dependant on the physical transmittance of the medium, but also dependent on the luminance of the medium, and its reflectance. It is then interesting to study the perceived transparency with a transparency model.

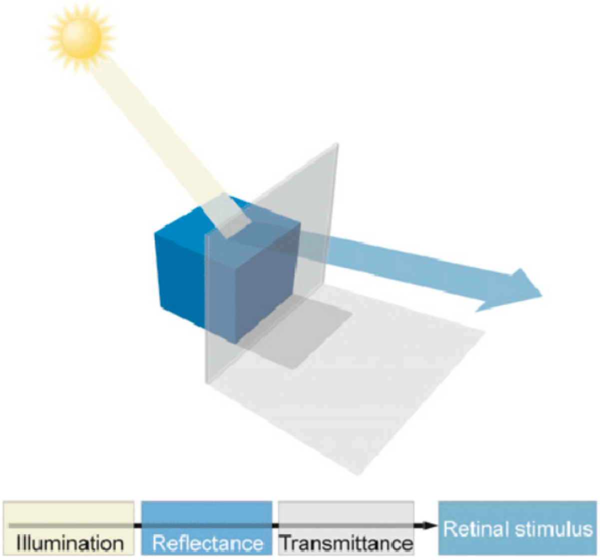


Figure 1: "The conflation of illumination, reflectance, and transmittance in retinal images". Taken from Purves et al. (2011).

1.2 Physical Model of Transparency: the Episcotister Model

There are different models of transparency. Here, I will explain the most used one: the episcotister model of transparency, which was introduced by Metelli (1970, 1974). An episcotister is a disk with a certain opening sector (its physical transmittance, α) and a certain luminance reflected by its surface (t). When it is rotated fast enough (approximately above 60Hz), it is perceived as a transparent disk as the visual system can not distinguish high temporal frequency (Figure 2). Although the disk is opaque and therefore it is impossible to be transparent, the human visual system recognizes it as transparent. Thus it can be said that the perceived transparency of a medium depends on its transmittance α and luminance t. Transmittance is a ratio of the incident intensity of light (I_0) to the amount of intensity that passes through the object (I)[1], basically, it is the ratio of light passing through the medium. The physical transmittance is calculated as follows:

$$T = \frac{I}{I_0} \tag{1}$$

In Figure 2 the transmittance α is shown as it represents the opening of the medium. Clearly, as the opening sector α increases, the disk will be perceived as more transparent because the amount of light that passes through the disk is higher.

The other variable influencing perceived transparency is the luminance t. According to the episcotisters model, the luminance of the background seen through the transparencies

[1] https://www.electrical4u.com/what-is-transmittance/

P and Q on different backgrounds are calculated as follows:

$$P = \alpha \cdot a + (1 - \alpha) \cdot t \tag{2}$$

$$Q = \alpha \cdot b + (1 - \alpha) \cdot t \tag{3}$$

where a and b are the luminances of the background without the transparency, t is the luminance reflected from the medium and α is the opening sector. As dark surfaces reflect less light than brighter surfaces, the luminance t of the dark surfaces is lower than bright surfaces. Accordingly, the lower the luminance is, the darker the medium looks.

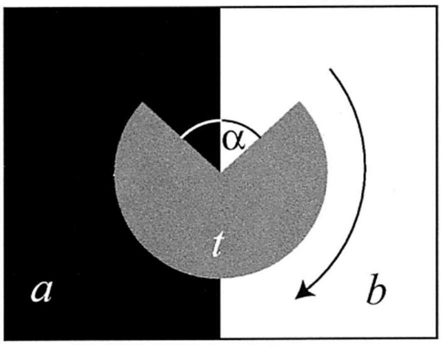


Figure 2: Metelli's episcotister model of transparency. Taken from Singh and Anderson (2002).

1.3 Perceived Transparency

When we assume that the episcotister model is a model of *perceived* transparency, it would predict that light and dark transparency would look equally transparent if they have the same transmittance α, because they would have the same amount of light passing through the medium. However, it is known that it is not the case.

Previous work showed that the perceived transparency of a medium depends on its background. Singh and Anderson (2002) observed that contrast is a "critical image variable that the visual system uses to assign perceived transmittance to transparent surfaces". As stimuli, they had large disks that contain vertical lines and are placed on a black background. Inside the large disk, a smaller disk with lower contrast was placed. In their experiment, the observers were shown a target disk and asked to adjust the luminance of the small disk, until its perceived transmittance was equal to the perceived transmittance of the target disk. Figure 3 shows an example of the procedure. Singh and Anderson (2002) found out that the perceived transparency of a transparent medium depends not only on its physical transmittance but also on the mean luminance reflected from the background that the medium covers.

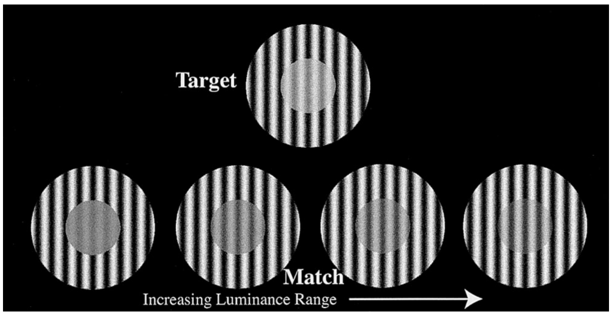
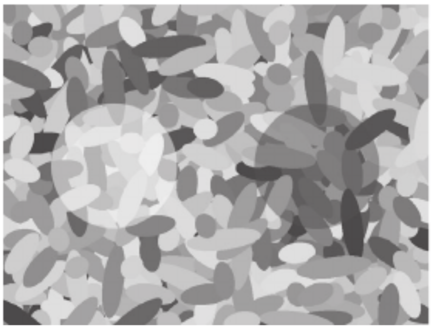


Figure 3: A demonstration of the transmittance-matching task of the experiment by Singh and Anderson (2002). The observers were asked to adjust the luminance of the small disk so that its perceived transparency matched the perceived transparency of the target disk. This was tested for different mean luminances.

Robilotto and Zaidi (2004) also investigated whether the perceived transparency depends on the background. An example of the stimuli they used can be seen in Figure 4. On the left side of each stimulus, there is a standard filter, with fixed transmittance and reflectivity, which is the reflection rate of a filter. The right side of each display had the match filter, and the observers were asked to adjust one property (transmittance or reflectivity) of the match filter until the perceived transparency of the standard and match filters were equal.

Transmittance is the amount of light that passes through the filter, whereas reflectivity is the amount of light reflected from it, similar to α and t from the episcotister model. In other words, if the transmittance of a filter is high enough, the filter appears transparent. Contrariwise, when the reflectance of the filter is high, the filter appears opaque.

The authors observed that decreasing the background's mean luminance or contrast decreases the perceived transparency of the filter and that the observers used the contrast when adjusting during the task until the perceived transparencies between the filters were equal. This shows that physically identical transparent media (filters) vary in the perceived transparency when they are located in front of backgrounds with different physical contrast and that the perceived transparency correlate with the perceived contrast of the medium. The results show that *reducing background contrast decreases the perceived transparency of the medium.*



(a) A uniform background

(b) Lower contrast background

Figure 4: Examples of stimuli Robilotto and Zaidi (2004) used in their experiments. The left side of each stimulus contains the standard filter with fixed transmittance and reflectivity values. The right side of each display contains the match filter and the observers adjusted one value while fixing the other one.

Aguilar and Maertens (2022) used maximum likelihood conjoint measurement (MLCM) to study the relationship between perceived transparency, perceived contrast, and image luminance. The authors used variegated checkerboards with partially covering transparent media varied in their transmittance α and luminance t. The transparent media were rendered stimulating the episcotister model, as can be seen in Figure 5.

Consider the case of two disks with equal opening α but different luminance t, one dark and one light (Figure 5B). Then it is clear that when the disks are rotated, they would have equal physical transparency. However, their perceived transparency varies. The dark one with lower luminance t is perceived as more transparent than the light one with higher t. Aguilar and Maertens (2022) observed that perceived transparency increases with increasing physical transmittance and decreases with increasing luminance. They found out that for two transparent media with equal physical transmittance, a dark one would always look more transparent than a bright one (Figure 5A).

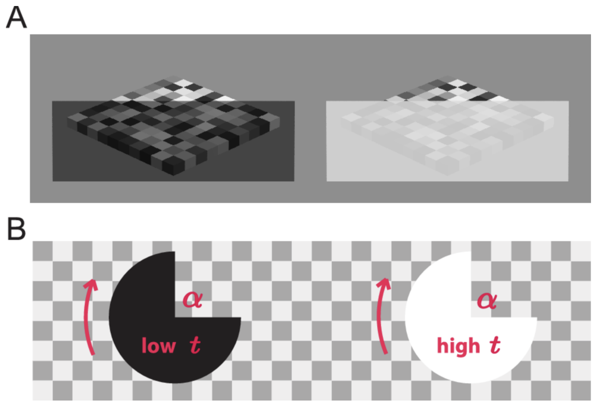


Figure 5: Episcotister Model
A: Two transparent media were rendered with varying luminance values t and equal transmittance α
B: Two episcotisters with identical openings α so that they have the same transmittance when rotated. The black one (low t) is perceived with higher transparency to the observers than the white one (higher t). t is the luminance reflected from the disk.
Taken from Aguilar and Maertens (2022)

Similar to Singh and Anderson (2002) and Robilotto and Zaidi (2004), Aguilar and Maertens (2022) also observed that perceived transparency seems to depend on perceived contrast.

The results mentioned above seem to indicate that *perceived contrast* is highly relevant to our perception of transparency. It is thus also relevant to review some aspects of what we know about contrast processing in the visual system

1.4 Contrast

Contrast is what makes an object distinguishable from other objects and the background. In human visual perception, contrast is calculated by the difference of the luminance values of the pixels (Maragatham & Roomi, 2015). In Figure 6 the difference between an image with low contrast and high contrast can be seen.

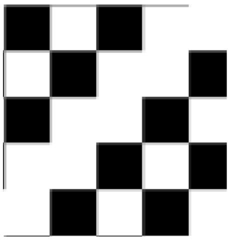
Figure 6: The image on the left side has a lower contrast than the image on the right side. Taken from https://blog.roboflow.com/when-to-use-contrast-as-a-preprocessing-step/

One way of quantifying contrast is by the following equation, known as Michelson contrast:

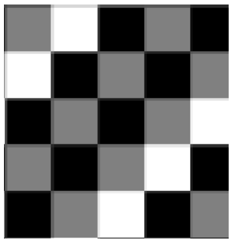
$$MC = \frac{l_{max} - l_{min}}{l_{max} + l_{min}} \tag{4}$$

where l_{max} and l_{min} are the highest and lowest luminance. The Michelson contrast equation is used in visual perception research using simple stimuli, such as gratings.

Since only the highest and the lowest luminance values are considered in the Michelson equation, it works better for images with two values of luminance, e.g. a checkerboard with black and white checkers. However, the Michelson contrast equation does not give the most accurate contrast value of an image consisting of more than two luminance values. Consider two checkerboards, one with two luminance values [0.0, 1.0] and the other with three [0.0, 0.5, 1.0]. The Michelson contrast equation will calculate the same contrast for both images, yet the perceived contrasts of the checkerboards might differ. Figure 7 shows two images with different luminance values but equal contrasts according to Michelson contrast equation (4).



(a) A checkerboard with two luminance values $[0.0, 1.0]$



(b) A checkerboard with three luminance values $[0.0, 0.5, 1.0]$

Figure 7: Example of checkerboards with different luminance values but equal Michelson contrasts. Although both stimuli have the same Michelson contrast, stimulus b appears to have less contrast than stimulus a.

Our perception of contrast is however more complex than the simple Michelson contrast equation. In fact, it is known that the background contrast also has an effect on the perceived contrast. In 1989 Charles Chubb and his colleagues observed the "contrast contrast illusion", where the perceived contrast of an object depends on the physical contrast of its background. They experimented with two physically identical disks with backgrounds with different contrasts. In Figure 8, it can be seen that the background of the left disk has the lowest contrast (zero-contrast) and the right disk has a higher contrast. The disks are identical, however, Chubb et al. (1989) observed that the *left disk with lower background contrast appears to have a higher contrast than the right one with higher background contrast to all observers.*

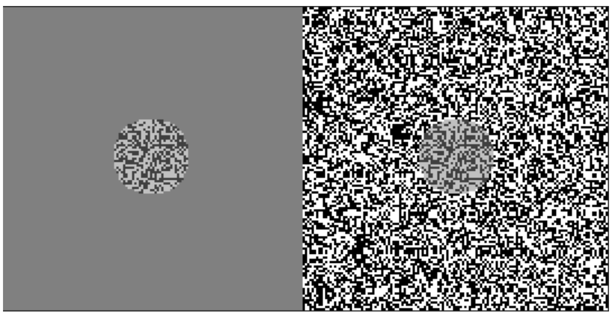


Figure 8: Two identical disks with different backgrounds. The background of the left disk has a lower contrast than the contrast of the background on the right. The one on the left appears to have higher perceived contrast.
Source: (Chubb et al., 1989)

1.5 Specific Motivation and Research Question

Chubb and his colleagues found that a lower background contrast causes a higher perceived contrast of the central disk (Chubb et al., 1989). Contrarily, Robilotto and Zaidi

(2004) observed that a lower background contrast leads to a lower perceived contrast and perceived transparency of the disk. These two findings seem incompatible with each other. Considering only the findings of Chubb et al. (1989), it is expected that a lower background contrast causes a higher perceived contrast of the medium, and accordingly a higher perceived transparency. In contrast, the findings of Robilotto and Zaidi (2004) would indicate otherwise; that a lower background contrast causes a lower perceived transparency of the medium, which would be associated with lower perceived contrast.

Here, I investigated the relationship between the background contrast and the perceived transparency of the medium. As mentioned above, it is known that perceived transparency is affected by its background, but so far no image metric or image statistic can predict our subjective perception. With that in mind, in my thesis, I evaluate metrics based on the contrast that could explain the perceptual effects. The goal is to find a metric that can predict the effect of the background contrast on the perceived transparency of the medium. In the following section, I present in detail the different contrast metrics used, based on the contrast literature. The evaluation of perceived transparency will be phenomenological, that is, by simply looking at the resulting stimuli.

In this thesis, I will particularly evaluate a contrast metric with the with the ratio R between the contrasts in the transparency region versus the background. Singh and Anderson (2002) observed that the ratio can predict perceived transparency, calculated as follows:

$$R = \frac{C_{TM}}{C_{BG}} \tag{5}$$

where C_{TM} and C_{BG} are the contrast of the transparent medium and the contrast of the background.

In this thesis, the physical contrast of the transparent medium is kept the same for every stimulus that has the same α and t values. For this reason, as the background contrast increases, the ratio decreases. In such a manner, for fixed α and t values, the ratio R_{HC} for high background contrast is lower than the ratio R_{LC} for low background contrast.

Considering all the findings mentioned above, it can be said that the ratio R, which is calculated in Equation 5, can be taken as a metric for perceived transparency. I hypothesize that as the ratio R decreases, the perceived transparency increases and that a high difference d between the ratios of two stimuli indicates that one of the stimuli seems to have strictly higher transparency than the other, whereas a lower difference suggests that the stimuli seem almost equally transparent. The difference d is calculated as follows:

$$d = R_n - R_m \tag{6}$$

where R_n and R_m stand for the ratios of n^{th} and m^{th} stimuli.

2 Methodology

This chapter details the methodological procedures taken in the present thesis. In the following, I first present a general overview of the procedure, and later each step is explained in detail.

First, different stimuli were rendered with varying background contrast c_{bg}, transmittance α, and luminance t. Afterward, I cut the transparent media with varying α and t values from the highest background contrast stimuli and pasted it on varying backgrounds. This step aimed to have the same transparent media for every background so that the effect of the background on the perceived transparency could be judged. In Figure 12 the process of cutting the transparent medium from the background with the highest background and pasting it on other backgrounds is sketched.

Following this step, for each rendered stimulus, I calculated the contrast of the background and the transparent medium for different contrast metrics. These metrics are Michelson contrast (MC), Space-Average Michelson contrast (SAM), Space-averaged logarithm of Michelson contrast (SAMLG), and Space-Average Whittle contrast (SAW). For these metrics, I calculated the ratio R between the contrast inside the transparent medium and the background contrast, and use the ratios to evaluate the metrics in order to find a metric that predicts the effect of the background contrast on perceived transparency better. I also calculated the difference d between the calculated ratios.

2.1 Initial Stimuli Creation

I generated variegated checkerboards with different physical contrasts in size of 22 x 22. In the middle of the checkerboard, a transparent medium with certain transmittance α and luminance t value was generated.

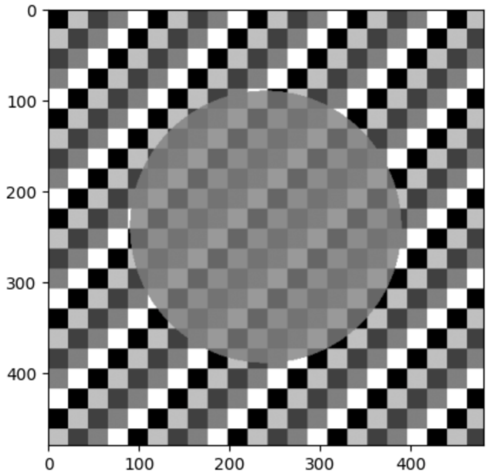


Figure 9: Example of stimuli with a variegated checkerboard with background contrast $c_{bg}(MC) = 1.0$, and a transparent medium with its transmittance $\alpha = 0.2$ and luminance $t = 0.5$ values.

For the background, randomly variegated checkerboards with five luminance values were rendered. To create various backgrounds with different contrasts, I created different vectors of five luminance values, where all values of luminance are relative between 0 and 1.0. The background contrast is calculated with Michelson Contrast equation (4) and background contrasts of the stimuli vary between 1.0 and 0.1. The luminance values used on the stimuli are [0.00001, 0.75, 0.25, 0.5, 1.0], [0.05, 0.725, 0.275, 0.5, 0.95], [0.1, 0.7, 0.3, 0.5, 0.9], [0.15, 0.675, 0.325, 0.5, 0.85], [0.2, 0.65, 0.35, 0.5, 0.8], [0.25, 0.625, 0.375, 0.5, 0.75], [0.3, 0.6, 0.4, 0.5, 0.7], [0.35, 0.575, 0.425, 0.5, 0.65], [0.4, 0.55, 0.45, 0.5, 0.6] and [0.45, 0.525, 0.475, 0.5, 0.55]. The background contrast decreases as the difference between the minimum and maximum luminance values l_{min}, l_{max} decreases.

For each checkerboard, five values of luminance were selected. The reason for this was that I wanted to evaluate the contrast metric MC, which is known to give better results when there are only two luminance values, as it is calculated with l_{min} and l_{max}. By increasing the luminance values to five, I aimed to examine whether MC can give accurate results when there are more than two luminance values.

The checkerboard is generated by taking a luminance value in the exact order from an array of five luminance values, as can be seen above. Thus, every stimulus has the same order of luminance values. For instance, if the first checker has the lowest luminance value, every background will have the lowest luminance value in the first checker. The reason for that is to ensure that the boundaries fit each other. As I create one transparent medium for a fixed transmittance α and a luminance t and paste it onto different backgrounds with varying contrast, it would be problematic if the order of the background and the pasted transparent media were different because in that case the boundaries would not align anymore and it would result in inconsistencies that could affect the perception of transparency. Figure 10 shows an example of inconsistency. Normally, a dark transparency can never make a dark checker lighter, as this is physically impossible. In order to prevent his issue, I created the background checkerboards with a fixed order.

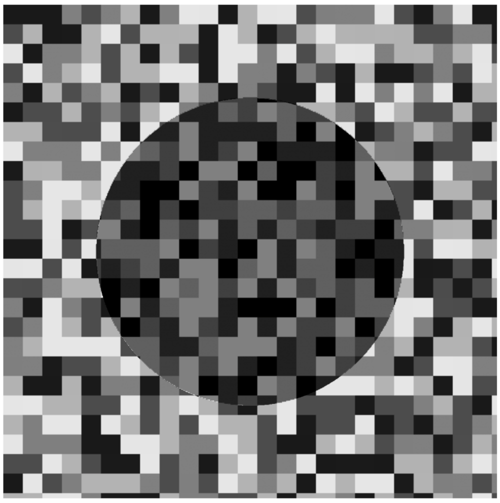


Figure 10: Example of stimuli where the boundaries of the background and the transparent medium do not align. An inconsistency can be seen on the checker that is located in the fifth column and fourteenth row.

Every possible combination for the transparent medium were designed with three values of α $(0.1, 0.2, 0.5)$ and four values of t $(0.0, 0.2, 0.5, 1.0)$. The background contrast varies between 0.1 and 1.0. In the initial stimuli creation phase, 120 stimuli were rendered in total.

2.1.1 Choice of Transmittance α

The transparent medium decreases the contrast of the area it covers and it is required that the physical contrast of the transparent medium is lower than the background contrast, otherwise, the transparent medium would never be perceived as transparent. Figure 11a shows an example of such an unwanted condition.

As the contrast inside the transparent medium is a function of $f(\alpha, t)$, therefore depends on the transmittance α and luminance t, it was important to select α and t carefully, to prevent the situation where the contrast inside the transparent medium is higher than the background contrast, otherwise, there would be no transparency to judge. I observed that this issue occurred while stimuli were rendered with high transmittance α values. For every background, the contrast inside the transparent medium with $\alpha = 0.9$ was higher than the background contrast, regardless of the luminance t. In Figure 11b the occurred problem can be seen. In order to prevent this, I excluded α values whereby a very high transparency is rendered, in this case, α values higher than 0.5. Hence, 0.1, 0.2, and 0.5 were chosen for transmittance α to have a minimal to middle transparency.

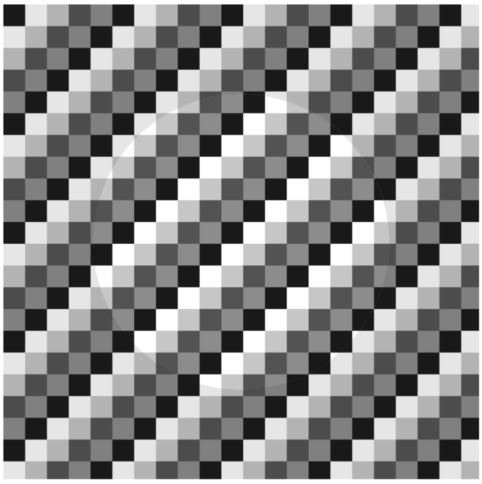


Figure 11: Example of stimuli where the background contrast is lower than the contrast inside the transparent medium. In this case, there is no transparency to be perceived. Transmittance α is 0.9, luminance t is 1.0 and the background contrast according to Michelson Contrast (MC) metric is 0.8.

2.1.2 Choice of Luminance t

As observed before, Aguilar and Maertens (2022) mentioned that "most observers perceive the light transparent medium as less transparent than the dark one, although both of them have the same physical transmittance". Thus it is expected that a transparent medium with low luminance t, e.g 0.0, would be perceived as more transparent than the medium with a high luminance value for instance 1.0. As it is necessary to examine both extreme situations, along with two medium luminance values, I decided to design the transparent media using 0.0, 0.2, 0.5, and 1.0 for the luminance.

2.2 New Background

As the goal of the experiment is to investigate the effect of the background contrast on the perceived transparency, I generated different backgrounds to a fixed transparent medium with a fixed transmittance and luminance. In order to achieve this, various transparent media with different α and t values were created on one background with fixed contrast, cut out, and pasted on variegated checkerboards with different background contrasts.

This process intends to keep the transparent medium the same while changing the background, thus preventing the change of contrast inside the medium so that the perceived transparency of the medium would be evaluated by only changing the backgrounds.

The transparent medium decreases the contrast of the area it covers and I wanted to keep the contrast in this area as high as possible. Keeping the decreased contrast in this area high allowed me to have more range of luminance values inside the transparent medium.

One idea was to cut out the transparent media from the backgrounds with the highest contrast $c_{bg}(MC) = 1.0$ and to paste them onto other backgrounds with decreasing contrasts. The methodology is sketched in Figure 12.

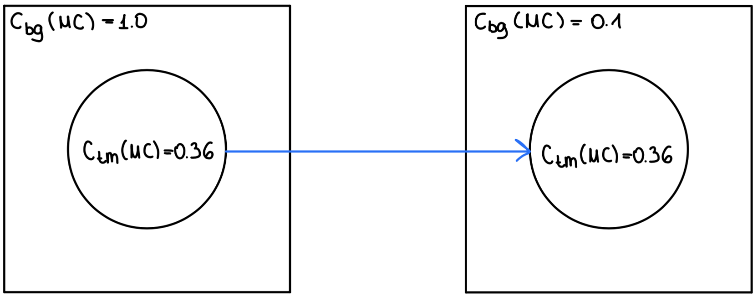
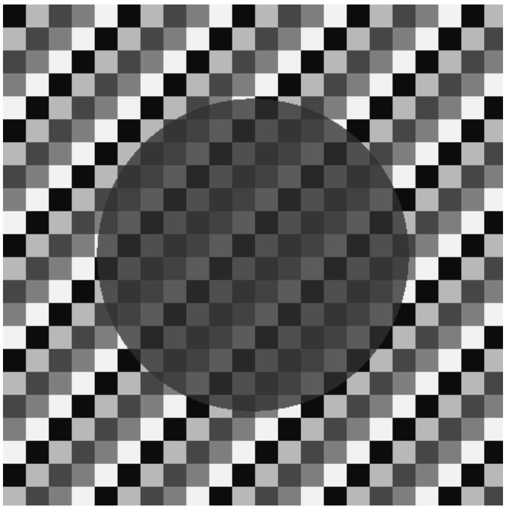
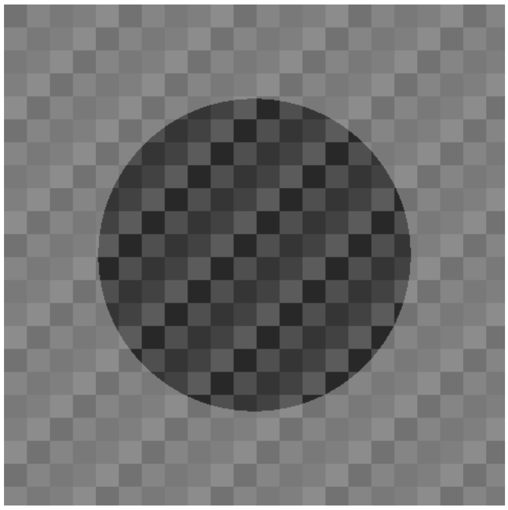


Figure 12: A sketch to explain how the transparent medium is cut and pasted on different backgrounds. On the left side a stimulus is rendered where the background has the highest contrast $c_{bg}(MC) = 1.0$ and the transparent medium has the contrast $c_{tm}(MC) = 0.36$.
On the right side a stimulus with the lowest background contrast $c_{bg}(MC) = 0.1$ can be seen. The transparent medium of the stimuli with the highest background contrast is cut out and pasted on the background with lower contrast.

However, I observed that in this case, in 63 stimuli out of 120, the contrast inside the transparent medium was higher than the background contrast. Assume the stimuli in which the transparent medium decreases the contrast of the area it covers from 1.0, which is the background contrast, to 0.36. When I cut and paste the transparent medium which has the contrast of $c_{tm}(MC) = 0.36$, it would be problematic when the background contrast is lower than 0.36. This situation caused problems because if the decreased contrast inside the transparent medium is higher than the background contrast, there would be no transparency to judge, as can be seen in (Figure 13b).



(a) Example of stimuli with background contrast $c_{bg}(MC) = 1.0$, and a transparent medium with its transmittance $\alpha = 0.2$ and luminance $t = 0.2$ values.



(b) Example of stimuli with background contrast $c_{bg}(MC) = 0.1$, and a transparent medium with its transmittance $\alpha = 0.2$ and luminance $t = 0.2$ values.

Figure 13: Example of two stimuli where the transparent media are cut out from the background with highest contrast $c_{bg}(MC) = 1.0$ and pasted onto other backgrounds.

In order to solve this, I created stimuli by cutting out the transparent media from the lowest background contrast with $c_{bg}(MC) = 0.1$, and pasting them onto varying backgrounds. By this method, the transparent medium decreases contrast from 0.5 This way, it was guaranteed that the transparent medium will have a lower contrast than the background contrast in every stimuli because the contrast inside the transparent medium will always be higher than the background contrast, as the contrast inside the transparent medium is nothing else than the decreased contrast of the background. This step is sketched in Figure 14.

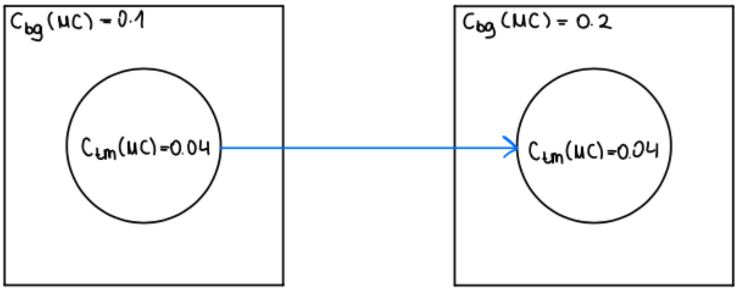
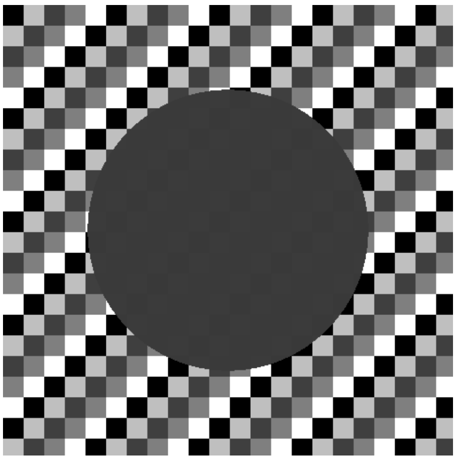
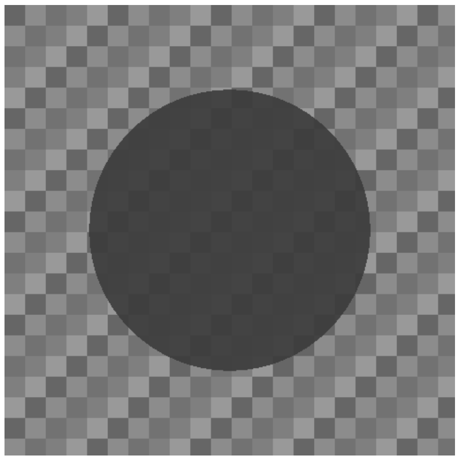


Figure 14: A sketch to explain how the transparent medium is cut and pasted on different backgrounds. On the left side a stimulus is rendered where the background has the lowest contrast $c_{bg}(MC) = 0.1$ and the transparent medium has the contrast $c_{tm}(MC) = 0.04$. On the right side a stimulus with different background ($c_{bg}(MC) = 0.2$) can be seen. The transparent medium of the stimuli with the lowest background contrast is cut out and pasted onto other backgrounds. As the transparent medium from the background with lowest contrast is lower than every background contrast, there is be no case where the background contrast is lower than the contrast of the transparent medium.

Yet, these stimuli were also problematic because the range of luminance values in the background and inside the transparent medium was too low and in the end, the transparent medium looked almost opaque which made the judgment of the transparency difficult This issue is visualised in (Figure 15).



(a) Example of stimuli with background contrast $c_{bg}(MC) = 0.1$, and a transparent medium with its transmittance $\alpha = 0.2$ and luminance $t = 0.2$ values.



(b) Example of stimuli with background contrast $c_{bg}(MC) = 0.1$, and a transparent medium with its transmittance $\alpha = 0.2$ and luminance $t = 0.2$ values.

Figure 15: Example of two stimuli where the transparent media are cut out from the background with highest contrast $c_{bg}(MC) = 1.0$ and pasted onto other backgrounds.

Consequently, I decided to take both types of stimuli into consideration and compare their ratios. I refer to the stimuli that had their transparent media taken from highest background as Set A, and to the stimuli that had their transparent media taken from lowest background as Set B.

2.3 Contrast Metrics and Ratio Calculation

For each stimulus, I calculated different contrast metrics for the inside of the transparent medium and for the background. I then calculated ratios between the transparent medium contrast and the background contrast for each contrast metric. The aim of this step is to evaluate the contrast metrics and to find a metric that can predict the effect of the background contrast on perceived transparency.

To calculate the contrasts inside the transparent medium and in the background separately, I created a mask with the exact shape and coordinates of the transparent medium. I then applied the mask to the numpy array, which consists of the luminance values for each checker of the stimulus ($22 * 22 = 484$), and created two arrays: one for luminance values inside the transparent region and one for the luminance values in the background. The metrics are calculated using these arrays in order to calculate the transparent medium contrast and background contrast separately.

I calculated four contrast metrics: Michelson contrast (MC), Space-averaged Michelson contrast (SAM), Space-averaged logarithm of Michelson contrast (SAMLG), and Space-averaged Whittle contrast (SAW), which were taken from Aguilar and Maertens (2022). The metrics are calculated as follows, whereby l_i refers to the luminance value of a checker and n to the number of luminance values in the area, in this case, 5:

1) Michelson contrast (MC)

$$MC = \frac{l_{max} - l_{min}}{l_{max} + l_{min}} \tag{7}$$

2) Space-averaged Michelson contrast (SAM)

$$SAM = \frac{1}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} \left| \frac{l_i - l_j}{l_i + l_j} \right| \tag{8}$$

3) Space-averaged logarithm of Michelson contrast (SAMLG)

$$SAMLG = \frac{1}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} log \left| \frac{l_i - l_j}{l_i + l_j} \right| \tag{9}$$

4) Space-averaged Whittle contrast (SAW)

$$SAW = \frac{1}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} \left| \frac{l_i - l_j}{min(l_i, l_j)} \right| \tag{10}$$

The metrics SAM, SAMLG, and SAW are space averaged metrics, meaning that the contrast calculation is done between all possible unique pairs of luminance values $(\forall i \neq j)$.

After the calculation of different metrics for each rendered stimulus, I calculated the ratio R between the contrast inside the transparency region and the contrast of the background. By this means, there were four ratios for each stimulus, R_{MC}, R_{SAM}, R_{SAMLG}, and R_{SAW}. The ratio R is calculated as follows:

$$R = \frac{c_t}{c_{bg}} \tag{11}$$

where c_t and c_{bg} are calculated with the same contrast metric.

If c_t and c_{bg} are calculated with MC, I referred to the ratio between these contrasts as R_{MC}, and equivalently for all other contrast metrics.

Because of the *logarithmic* function in Equation 9, every result of the contrast metric (SAMLG) resulted in negative values. For instance, the contrast metrics $SAMLG$ on stimulus with highest background contrast and $\alpha = 0.1$, $t = 0.1$, are calculated negative ($c_{bg}(SAMLG) = -0.494$, $c_{tm}(SAMLG) = -1.687$). The condition of the contrast of the transparent medium being lower than the background contrast is met ($-1.687 < -0.494$), the ratio, however, is higher than 1.0 ($\frac{c_{tm}(SAMLG)}{c_{bg}(SAMLG)} = 3.414$), which is interpreted as "no transparency perception" of the transparent medium, which is actually not the case. Figure 16 shows the mentioned stimulus.

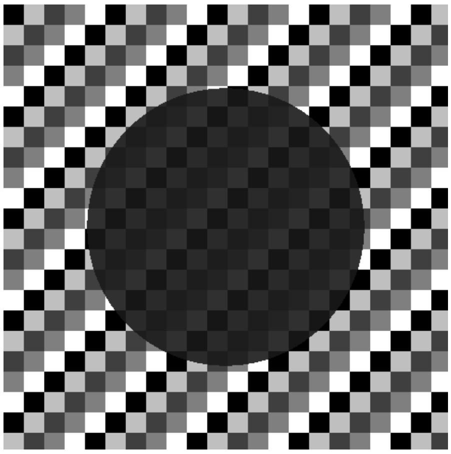


Figure 16: The stimulus with highest background contrast and $\alpha = 0.1$, $t = 0.1$ and contrast metric $SAMLG$ results in negative values: $c_{bg}(SAMLG) = -0.494$, $c_{tm}(SAMLG) = -1.687$.

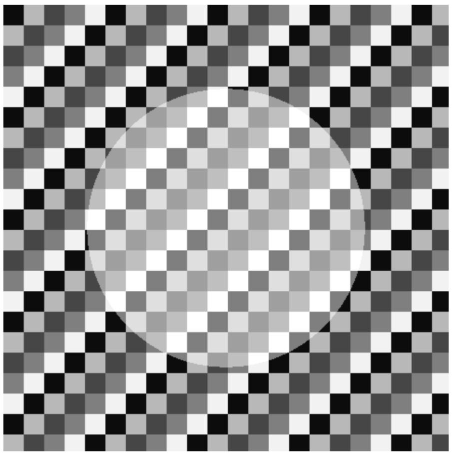
In order to prevent this issue from happening, I shifted up the SAMLG values by summing every value with the minimum value of all calculated $SAMLG$ contrast metric values, so that the minimum value would be equal to zero. The ratios R between the contrast inside the transparent medium and the background contrast with the SAMLG contrast metric are calculated with the summed-up values.

As the ratio is nothing else than the division of the transparent medium contrast to the background contrast, a ratio higher than 1.0 means that the contrast of the transparent medium is higher than the one of the background. As a result, a transparent medium of a stimulus with a ratio higher than 1.0 would never be perceived transparent. On the contrary, it will be seen as almost opaque (Figure 13b). As the transparent media contrasts are always lower than the background contrasts when the transparent media are taken from the lowest background contrast, every ratio, regardless of the used contrast metric, is lower than 1.0. This means that I was able to use every 120 stimuli which have their transparent media taken from the lowest background contrast. However, this was not the case when the transparent media are taken from the highest background contrast. I observed that when the ratios were calculated with MC, SAM, and SAW contrast metrics, there were 40 stimuli that had ratios higher than 1.0. But when the ratios were calculated with $SAMLG$, 63 stimuli had ratios higher than 1.0. 40 stimuli being already included in the 63 stimuli, I excluded the 63 stimuli out of the comparison, which implies that I was able to use 57 stimuli that had their transparent media from the highest background contrast.

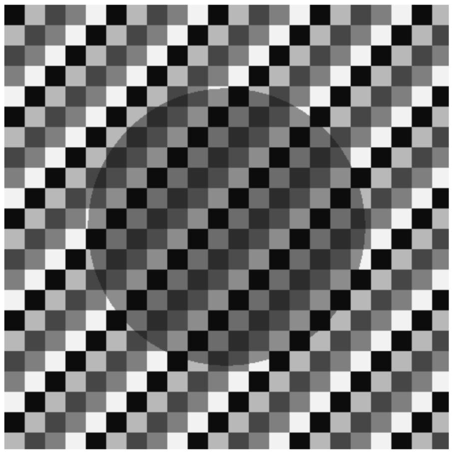
2.4 Comparison with Subjective Perception

The final step is the comparison of the stimuli with my subjective impression. I did not conduct an experiment because I first wanted to find out if there is an effect between the background contrast and the perception of transparency and if there is a contrast metric that can predict my transparency perception, before conducting an experiment. Therefore, I only compared the stimuli with my subjective perception. I observed two stimuli side by side and judged the perceived transparency by answering the question: which of the two transparent media looked more transparent? Figure 17 shows an example of one trial of comparing two stimuli.

The idea is to compare two stimuli at once visually, and then to compare their ratios for every contrast metric to evaluate if a contrast metric can predict the effect of the background on the perception of the transparency and if the answer is yes, which metric predicts the effect better.



(a) Example of stimuli with background contrast $c_{bg}(MC) = 1.0$, and a transparent medium with its transmittance $\alpha = 0.5$ and luminance $t = 1.0$ values.



(b) Example of stimuli with background contrast $c_{bg}(MC) = 1.0$, and a transparent medium with its transmittance $\alpha = 0.5$ and luminance $t = 0.1$ values.

Figure 17: **Which stimulus appears to have more transparency?**
Example of one trial of comparing two stimuli visually.

In each trial I judged the perceived transparencies between the two stimuli and used a five-level Likert scale to judge, which is as follows:

1. The first stimulus appears to have much more transparency.
2. The first stimulus appears to have a little more transparency.
3. They seem the same.
4. The second stimulus appears to have a little more transparency.
5. The second stimulus appears to have much more transparency.

After each judgment of the two stimuli on their perceived transparency, I compared their ratios with different metrics, R_{MC}, R_{SAM}, R_{SAMLG} and R_{SAW} and the difference d of the ratios of the compared stimuli for each contrast metric. The goal of this comparison was to evaluate the contrast metrics and to find out which metric predicts the effect between the background contrast and the transparency perception better. In this step, I expected the ratio R and difference d to correlate with my answers for the five-level Likert scale. For instance, if I answered 1. in a trial, I expected the difference d between the contrast metrics of the stimuli to be very high. On the contrary, if I judged the stimuli to appear to have the same transparency and gave the answer 3., I expected the difference between the metrics to be very low, almost zero.

3 Results

3.1 Effect of Changes in Physical Transmittance α

The first thing I checked was the effect of physical transmittance α on perceived transparency. As expected, I observed that the perceived transparency increased with increasing physical transmittance, in every combination of physical transmittance α, luminance t, and background contrast c_{bg}. The reason for this relation was that with increasing transmittance, the amount of light getting through the transparent medium increased, which increases the physical transparency.

In Table 1, examples of stimuli with varying physical transmittance α with identical background contrast c_{bg} and luminance t are shown. The transparent media of the first four stimuli in the first two rows were cut out and pasted from the highest background contrast and the transparent media of the stimuli in the last two rows were cut out from the lowest background contrast. I observed that regardless of the background contrast the transparent media are taken from, the background contrast, and the luminance t of the stimuli, the perceived transparency increased as the physical transmittance α increased.

I observed that the stimulus that is perceived as more transparent than the stimulus it is compared to, has a higher ratio, except the stimuli that have their transparent medium taken from the lowest contrast and their ratios calculated with SAW. I also noticed that ratios calculated with $SAMLG$ resulted in higher values than the ratios calculated with other contrast metrics, which was also identified as one of the best-fitting metrics by Aguilar and Maertens (2022).

However, I recognized was that there was no pattern between the difference between ratios calculated with $SAMLG$ and the perceived transparency of the stimuli. To my subjective perception, the second stimulus in the second row seems strictly more transparent than the first stimulus, and the second stimulus in the third row seems slightly more transparent, with a little difference between the perceived transparencies. Then, I compared the difference d between the ratios of the compared stimuli. I observed that the difference d_{SAMLG} of stimuli in the third row is higher than the difference d_{SAMLG} of stimuli in the second row. On the other hand, for every other contrast metric (MC, SAM, SAW), there was a clear pattern. When there is a significant difference between the perceived transparencies, the difference between the ratios (d_{MC}, d_{SAM}, d_{SAW}) was higher.

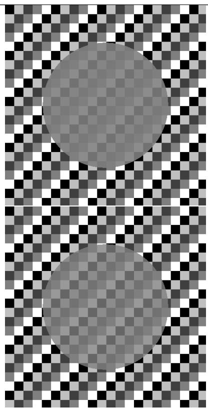
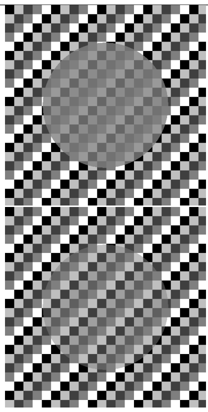
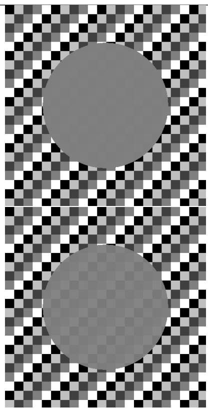
	$t = 0.5$	α	TM taken from	R_{MC}	d_{MC}	R_{SAM}	d_{SAM}	R_{SAMLG}	d_{SAMLG}	R_{SAW}	d_{SAW}	Subjective Impression
$c_{bg} = 1.0$		0.1 0.2	$c_{bg} = 1.0$	0.1 0.2	0.1	0.08 0.16	0.08	0.23 0.51	0.28	0.004 0.009	0.005	5.
$c_{bg} = 1.0$		0.2 0.5	$c_{bg} = 1.0$	0.2 0.5	0.3	0.16 0.42	0.26	0.51 0.89	0.38	0.01 0.03	0.02	5.
$c_{bg} = 1.0$		0.1 0.5	$c_{bg} = 0.1$	0.01 0.05	0.04	0.01 0.04	0.03	0.11 0.63	0.52	0.001 0.002	0.001	5.

Table 1: Perceived transparency increases with increasing transmittance α values on different backgrounds. The stimuli in the first two rows have their transparent media taken from the highest background contrast $c_{bg} = 1.0$, whereas the transparent media of the stimuli in the last row are taken from the lowest background contrast $c_{bg} = 0.1$, TM is the abbreviation for transparent medium, and d stands for the difference between the ratios of two compared stimuli.

3.2 Effect of Changes in Luminance t Inside the Transparent Medium

Afterward, I investigated the effect of luminance t on the perceived transparency of the transparent medium. The Table 2 shows examples of stimuli on which the effect of varying luminance t is investigated. Transparent media of the shown stimuli are taken from the background with the highest contrast.

It was observed in the previous work by Aguilar and Maertens (2022) that the perceived transparency increases with decreasing luminance t. I investigated backgrounds with contrast values of $0.0, 0.6$, and 1.0 and with varying transparent media with luminance values of $0.1, 0.2, 0.5$, and 1.0, as well as with $0.1, 0.2$ transmittance values. I also investigated the effect of the luminance on the transparency perception of the transparent media that are cut out from backgrounds with the highest and lowest contrasts.

According to my subjective inspection, in most of the combinations of background contrast, luminance t, and transmittance a, the transparent media with lower luminance t which are taken from the background with the lowest contrast, are perceived as more transparent than the transparent media with higher luminance t. Additionally, when the background contrast is higher than 0.7, the perceived transparency increases with decreasing luminance t, which was expected as it was investigated in previous work. This effect can be seen in Table 2 on first and third rows.

However, I observed some contradictory results in some cases, that the transparent media with higher luminance t appeared to have slightly more transparency than with lower luminance t. For instance, when the background contrast is equal lower than 0.7, the transparent media with higher luminance t, except when it was 1.0, appeared to have more transparency when compared with transparent media with lower luminance t. I also observed that the stimuli with lower luminance t have a higher ratio R with every contrast metric calculation. On second and fourth rows in Table 2, the effect can be seen.

Additionally, I observed more difference between the transparencies of two stimuli with background contrasts equal lower to 0.7 when one of the stimuli has luminance $t = 0.5$. For example, I inspected that the second stimulus in the last row seemed *strictly* more transparent than the first stimulus. On the other hand, the second stimulus in the second row seemed *slightly* more transparent than the stimulus it was compared to. I examined that with identical backgrounds, the differences between the ratios of MC and SAM contrast metrics were almost equal, and the differences between the ratios of SAW were almost equal when the background was higher than 0.7. On the other hand, I observed that the differences between the ratios of $SAMLG$ increased as I observed more differences between the transparencies. As mentioned above, I observed a vast difference between the transparencies of stimuli with background contrasts lower equal than 0.7 and one of them has luminance $t = 0.5$, comparing with other stimuli comparison that is shown in the Table 2. It is worth mentioning that the pair of stimuli, where I observe a big difference between the transparency perception, has a higher d_{SAMLG} than the other pairs.

Further, I compared the ratios R from Table 1 and Table 2. I observed that stimuli that seem to have high transparency, have a high ratio when I was adjusting the transmittance α. However, such a relation was not observed when I changed the luminance t of the stimuli. The second thing I noticed was, that I observed a more noticeable change of transparency between stimuli with different transmittance α than between stimuli with different luminance t. Yet, there was no relation between this and their ratios and their differences d. In fact, in some cases, the difference between the ratios of the former mentioned stimuli was lower than the difference between the ratios of the latter. The only contrast metric, for which the difference between the ratios was higher when the change of transparency is more noticeable, was $SAMLG$.

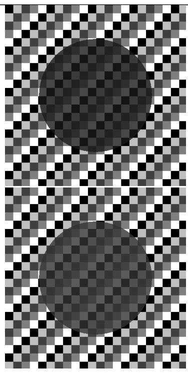
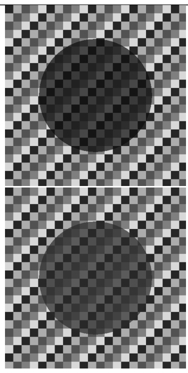
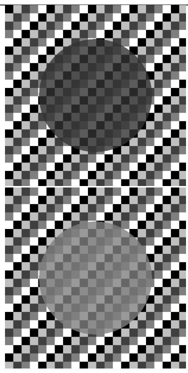
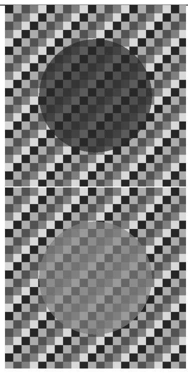
	α=0.2	t	R_{MC}	d_{MC}	R_{SAM}	d_{SAM}	R_{SAMLG}	d_{SAMLG}	R_{SAW}	d_{SAW}	Subjective Impression
$c_{bg} = 1.0$		0.1 0.2	0.56 0.38	0.18	0.48 0.32	0.16	0.94 0.78	0.16	0.04 0.02	0.02	2.
$c_{bg} = 0.7$		0.1 0.2	0.8 0.54	0.26	0.77 0.52	0.25	1.16 0.96	0.2	0.59 0.33	0.26	4.
$c_{bg} = 1.0$		0.2 0.5	0.38 0.2	0.18	0.32 0.16	0.16	0.78 0.51	0.27	0.02 0.01	0.01	2.
$c_{bg} = 0.7$		0.2 0.5	0.54 0.29	0.25	0.52 0.26	0.26	0.96 0.63	0.33	0.33 0.14	0.19	5.

Table 2: Perceived transparency increases with decreasing luminance t when the background contrast is higher than 0.7; but increases with increasing luminance t (except when $t = 1.0$) when the background contrast is equal lower than 0.7. The transparent media were taken from the highest background contrast $c_{bg} = 1.0$ d stands for the difference between the ratios of two compared stimuli.

3.3 Effect of Background Contrast c_{bg}

Interesting observations were made when I compared the transparencies of the stimuli with varying backgrounds. Firstly, I compared the stimuli for those transparent media taken from the highest background contrast $c_{bg} = 1.0$ (Set A), then the stimuli with transparent media taken from the lowest background contrast $c_{bg} = 0.1$ (Set B). I will start with the results of the first comparison (Set A).

I noticed that some stimuli seemed not transparent although their ratios were lower than 1.0. These background contrasts of these stimuli were lower than 0.6.

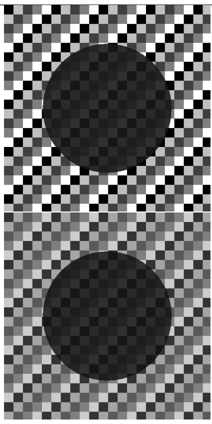
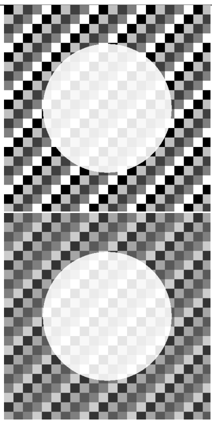
t	$\alpha = 0.1$	c_{bg}	TM taken from	R_{MC}	d_{MC}	R_{SAM}	d_{SAM}	R_{SAMLG}	d_{SAMLG}	R_{SAW}	d_{SAW}	Subjective Impression
0.1		0.1 0.7	1.0	0.36 0.51	0.15	0.3 0.49	0.19	0.75 0.93	0.18	0.02 0.3	0.27	3.
1.0		0.1 0.7	1.0	0.05 0.07	0.02	0.05 0.07	0.02	0.0 0.0	0.0	0.002 0.048	0.046	3.

Table 3: For both comparisons (row 1 and row 2), the stimuli seemed the same. When the luminance t is high (1.0), the ratios R and the differences d between the ratios for each metric are low. However, this was not the case when luminance was lower. (TM is the abbreviation for transparent medium, and d stands for the difference between the ratios of two compared stimuli.)

Moreover, for almost half of the combinations of α and t, I did not perceive a difference between the stimuli with varying backgrounds. These combinations were (t = 0.1, α = 0.1), (t = 0.2, α = 0.2), (t = 0.5, α = 0.5), (t = 1.0, α = 0.1) and (t = 1.0, α = 0.2). In Table 4 examples of stimuli that looked almost equally transparent can be seen. There was no correlation found between the transparency perception and the ratios, for every contrast metric. Additionally, although both pairs of stimuli appeared the same, the differences between the ratios were substantial. For instance, d_{SAW} in the first row is 0.27, but 0.046 in the second row. As there was no difference between the perceived transparencies for both comparisons, it was assumed that the difference d would be approximately zero. Thus it can be said that the differences d between the ratios R do not correlate with the differences between the perceived transparencies.

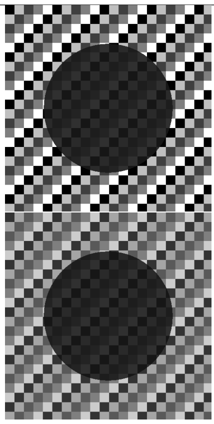
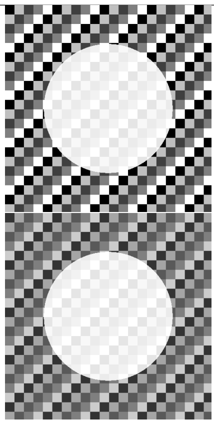
t	$\alpha = 0.1$	c_{bg}	TM taken from	R_{MC}	d_{MC}	R_{SAM}	d_{SAM}	R_{SAMLG}	d_{SAMLG}	R_{SAW}	d_{SAW}	Subjective Impression
0.1		0.1 0.7	1.0	0.36 0.51	0.15	0.3 0.49	0.19	0.75 0.93	0.18	0.02 0.3	0.27	3.
1.0		0.1 0.7	1.0	0.05 0.07	0.02	0.05 0.07	0.02	0.0 0.0	0.0	0.002 0.048	0.046	3.

Table 4: For both comparisons (row 1 and row 2), the stimuli seemed the same. When the luminance t is high (1.0), the ratios R and the differences d between the ratios for each metric are low. However, this was not the case when luminance was lower. (TM is the abbreviation for transparent medium, and d stands for the difference between the ratios of two compared stimuli.)

During the comparison, I observed two main effects, which are illustrated in Table 5. First, with the combination of $\alpha = 0.1$, $t = 0.2$, I noticed that with increasing background contrast, the perceived transparency increased. This result was consistent with the findings of Robilotto and Zaidi (2004), that a high background contrast would cause a high perceived transparency of the medium. However, the latter effect contradicted Robilotto and Zaidi (2004)'s findings. I observed that there when the luminance t of the transparent medium was 0.5 and transmittance α was lower than 0.5, the stimuli with lower background contrast looked much more transparent than those with higher background contrast. A similar effect was also observed with the combination of $t = 1.0$, $\alpha = 0.5$, but there was a slight difference between the transparencies. The first row shows the stimuli with luminance $t = 0.2$ with varying backgrounds. I observed that the stimulus with higher background contrast seem more transparent than the stimulus with lower background contrast and this observation agreed with Robilotto and Zaidi (2004)'s results. The stimuli in the second row shows a contradictory result, that a perceived transparency increased with decreasing background contrast. This observation agreed with Chubb et al. (1989)'s findings.

Comparing the ratios of stimuli for which the transparency perception increased with decreasing background contrast, I realized that ratios for every contrast metric were increasing with increasing transparency perception. However, this was not the case with the stimuli for which the transparency perception increased with increasing background contrast. In this case, the ratios of the stimuli, which seemed less transparent were higher than the ones with higher transparency.

I noticed a correlation between the differences in transparency perceptions and the differences in ratios d. As one stimulus seemed to have strictly more transparency than the other, the difference between their ratios was higher than the one for which the difference between the transparencies was not that obvious. For instance, when comparing the first two stimuli in the second row (Table 5), I do not perceive a vast difference between the transparencies, and the d_{SAMLG} is 0.29 - 0.23 = 0.06. When comparing the first and third stimuli, it is obvious that the third stimulus appear more transparent, and d_{SAMLG} between these stimuli is calculated as 0.18. This indicates that the difference between the ratios d does correlate with the difference in transparency perception of the compared stimuli.

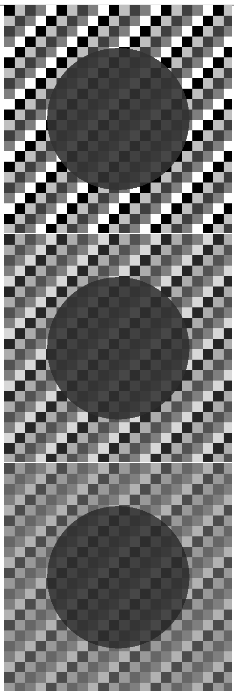
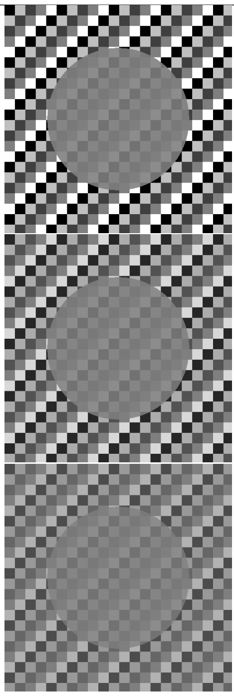
t	$\alpha = 0.1$	c_{bg}	R_{MC}	d_{MC}	R_{SAM}	d_{SAM}	R_{SAMLG}	d_{SAMLG}	R_{SAW}	d_{SAW}	Subjective Impression
0.2		1.0	0.22	0.33	0.18	0.36	0.55	0.42	0.01	0.45	1.
		0.7	0.31		0.29		0.68		0.158		
		0.4	0.55		0.54		0.97		0.46		
0.5		1.0	0.1	0.15	0.08	0.17	0.23	0.18	0.004	0.187	5.
		0.7	0.14		0.13		0.29		0.066		
		0.4	0.25		0.25		0.41		0.191		

Table 5: In the first row, it can be seen that perceived transparency increases with increasing background contrast. However, perceived transparency of the stimuli in the second row decreased with increasing background contrast. The shown stimuli are part of Set A. d stands for the difference between the ratios of the stimuli with highest and the lowest background contrast.

Similar observations were made when comparing the stimuli which had their transparent media taken from the lowest background contrast $c_{bg} = 0.1$.

First of all, I noticed that as the contrast of the transparent media was lower than 0.1, there were some combinations for which the transparent media appeared almost opaque, hence no difference between the transparencies could be judged. These combinations were ($t = 0.1$, $\alpha = 0.1$), ($t = 0.1$, $\alpha = 0.2$), ($t = 0.2$, $\alpha = 0.1$), ($t = 0.2$, $\alpha = 0.2$), ($t = 0.5$, $\alpha = 0.1$), ($t = 0.5$, $\alpha = 0.2$), ($t = 1.0$, $\alpha = 0.1$), ($t = 1.0$, $\alpha = 0.2$), ($t = 1.0$, $\alpha = 0.5$). Table 6 shows examples of mentioned stimuli. It is clear that when the luminance t was 1.0, there was no transparency to be judged. It is also straightforward that when the transmittance α is not high enough, meaning lower than 0.5, the transparent media seemed opaque, which made the observation impossible.

It can be said that when the transparent media were perceived as almost opaque, and the stimuli appeared the same, the ratios and the differences between them were relatively low, except when they were calculated with the contrast metric $SAMLG$. The only combination for which R_{SAMLG} and d_{SAMLG} were also low, was when t was 1.0, as can be seen in the second row in Table 6.

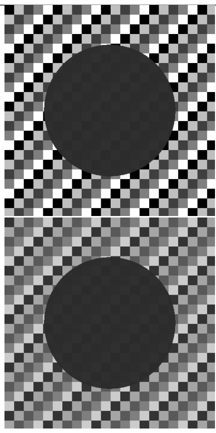
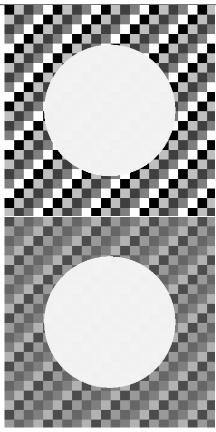
		α	$c_{bg}(MC)$	R_{MC}	d_{MC}	R_{SAM}	d_{SAM}	R_{SAMLG}	d_{SAMLG}	R_{SAW}	d_{SAW}	Subjective Impression
$t = 0.1$		0.2	1.0 0.6	0.06 0.1	0.04	0.05 0.09	0.04	0.72 0.97	0.25	0.002 0.054	0.052	3.
$t = 1.0$		0.1	1.0 0.4	0.01 0.02	0.01	0.01 0.02	0.01	0.0 0.0	0.0	0.0002 0.004	0.0038	3.

Table 6: The transparent media seem opaque, and the compared stimuli seem the same. The shown stimuli are part of Set B, d stands for the difference between the ratios of two compared stimuli.

For all remaining combinations, the transparent media seemed transparent and I observed that with increasing background contrast, the transparency perception decreased. This observation agreed with the findings of Chubb et al. (1989), that a lower background contrast would cause a higher perceived transparency. An example of this effect can be seen in the in Table 7. There is no doubt that the ratios of the stimuli that appeared to have strictly more transparency than the stimuli they are compared to, are higher. It is also noteworthy that the differences d_{MC}, d_{SAM}, and d_{SAW} are relatively small, although one stimulus seemed to have a lot more transparency than the other. The only contrast metric for which the difference between the ratios was high, was $SAMLG$.

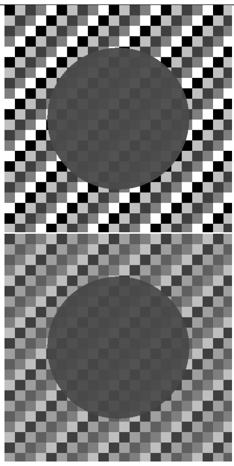
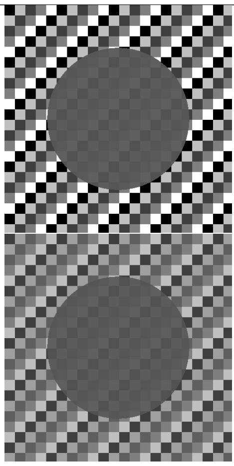
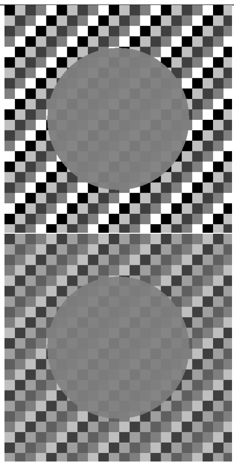
t	$\alpha = 0.5$	c_{bg}	R_{MC}	d_{MC}	R_{SAM}	d_{SAM}	R_{SAMLG}	d_{SAMLG}	R_{SAW}	d_{SAW}	Subjective Impression
0.1		1.0 0.5	0.08 0.16	0.08	0.07 0.16	0.09	0.84 1.28	0.44	0.003 0.107	0.104	5.
0.2		1.0 0.5	0.07 0.14	0.07	0.05 0.13	0.08	0.75 1.15	0.4	0.003 0.092	0.089	5.
0.5		1.0 0.5	0.05 0.1	0.05	0.04 0.09	0.05	0.63 0.95	0.32	0.002 0.045	0.043	5.

Table 7: Perceived transparency decreased with increasing background contrast. The shown stimuli are part of Set B, d stands for the difference between the ratios of two compared stimuli.

4 Discussion

I studied whether the perceived transparency of the medium increases with increasing background contrast. I also investigated whether the ratio R between the contrast of transparent medium and background contrast correlates with perceived transparency, as proposed by Singh and Anderson (2002). Further, I examined whether a high difference d between the ratios of two stimuli indicates that one of the compared stimuli seems to have strictly higher transparency than the other, whereas a lower difference suggests that the stimuli seem almost equally transparent. To study these, I used stimuli that have a random variegated checkerboard as the background and a transparent medium in front of it. I varied the luminance t and transmittance α of the transparent media and the background contrast c_{bg}. I calculated the ratio between the contrast of the transparent medium and background contrast with different contrast metrics. To examine, I used 177 stimuli in total: 57 had their transparent media taken from the background with the highest contrast (Set A), and 120 from the background with the lowest contrast (Set B).

I conducted the study in two examinations. First, I observed the transparency perception of the stimuli from Set A, then from Set B. The results of the first investigation show that there is no clear correlation between the background contrast and the transparency perception of the transparent media as there are contradictory effects observed. In some cases, the transparency perception decreased with increasing transparency, as Chubb et al. (1989) observed, and in some cases the opposite, as Robilotto and Zaidi (2004) investigated. Table 5 shows the stimuli where contradictory effects are observed. The reason for the contradictory results might be the differences in the choice of backgrounds. Robilotto and Zaidi (2004) used a randomly generated background consisting of randomly sized, overlapping ellipses. The observers of Chubb et al. (1989)'s experiment investigated the perceived transparency on two different backgrounds: one was a solid background with zero contrast and the other was a random variegated background with two luminance values. The background I used was a randomly generated checkerboard and I varied the background contrast by adjusting the luminance. The fact that every stimulus has the same order of luminances might be the reason for contradictory observations.

This observation, that there are combinations where the effect agrees with Robilotto and Zaidi (2004)'s, and the rest agrees with Chubb et al. (1989)'s findings, is interesting. It might be that for some combinations of α, t and background contrast, one can replicate Robilotto and Zaidi (2004)'s effect, but this is not a general thing.

Additionally, there was no correlation found between the ratio and perceived transparency. I observed that for every contrast metric, the ratio decreases with increasing luminance t of the transparent medium. The reason for that is that the transparent medium with high luminance t increases the luminance of the area it covers and therefore decreases the contrast of the area; whereas the transparent medium with low luminance t decreases the luminance and has less effect on the contrast of the area.

The transparent medium with low luminance has a higher contrast than the one with higher luminance because the area it covers with low luminance has a wider range of luminances compared to the area covered by the higher luminance transparent medium. Hence, the more the transparent medium decreases the contrast, the lower the ratio. In consequence, I am of the opinion that the ratio R can be a metric of contrast perception, rather than transparency perception.

An interesting observation was that the difference between the perceived transparencies correlated with the difference between the ratios of the stimuli, d. The difference d between the ratios is high when the difference between the transparencies is more obvious and vice versa. When I compared the ratios between two stimuli with the same transparent media, the only variable that was different between these two is the background contrast. Assume we have two pairs of stimuli being compared: a is being compared to b and c to d. Presume that a seems to have much more transparency than b, but c and d seem the same. In this situation, the difference between the ratios of a and b is higher than the of c and d. This observation could be interpreted as follows: the difference between the ratios of two stimuli indicates the difference between their perceived transparency.

On the other hand, this interpretation contradicts the previously mentioned observation, that the ratio has no correlation with perceived transparency. The reason for the contradiction might be that I do not have enough data as I collected the data with an evaluation of perceived transparency as they appear in my experience, instead of conducting an experiment with multiple observers. Furthermore, there might be errors with the data I have. Hence, I can not draw further conclusions about the relationship between the ratio and perceived transparency with the particular 57 stimuli of Set A.

Next, I studied the transparency perception of the stimuli of Set B. Using these stimuli was difficult, as more than half of the transparent media did not seem transparent. The reason behind that is the fact that the contrast of the transparent media is in every combination lower than 0.1, which resulted in the media appearing almost opaque. There was no transparency to be judged when the luminance t is 1.0, or the transmittance α is lower than 0.5. The first can be explained with the findings of Aguilar and Maertens (2022), that perceived transparency decreases with increasing luminance. The latter effect can be explained by the effect of transmittance on physical transparency. As the opening of the medium α gets bigger, more light gets through the medium, which results in more physical transparency. Keeping the transmittance α low at 0.1 or 0.2 leads to low physical transparency. This, together with the fact that the contrast of the transparent media is very low, results in transparent media appearing opaque.

I observed with stimuli from Set B that when the transparent media seem opaque, the ratios and their differences (except $SAMLG$) were very low, approximately zero. It can be stated, that when the transparent media are taken from the lowest background contrast, the ratios correlate with the perceived transparencies of the transparent media. As there was no transparency to be judged, it was expected the ratios to be considerably low, which was the case with the ratios that are calculated with contrast metrics MC, SAM, and SAW. The metric $SAMLG$ could not predict the perceived transparency except when the luminance t was 1.0. This observation contradicts the findings of Aguilar and Maertens (2022). What they found out was that two metrics, "$SAMLG$ [...] predicts constant differences of perceived transparency". Contrariwise, I observed that $SAMLG$ did not predict differences in perceived transparency. The only stimuli where $SAMLG$ predicted the constant differences of perceived transparency was when the luminance t was 1.0. The reason for that is that the media with $t = 1.0$ decreases the contrast of the area it covers considerably, and the contrast of the area decreases to approximately zero, which results in a ratio to be calculated almost zero. This does not happen when the luminance is lower, because transparent media with lower luminance t do not decrease the contrast of the area they cover as much as the transparent media with luminance 1.0. Hence, the ratios of stimuli with lower luminance were higher than the with higher luminance.

I observed with the rest of the stimuli of Set B, where there was a transparency to be judged, that the perceived transparency increased with decreasing background contrast. Table 7 shows examples of stimuli where this effect is examined. This observation corresponds with the findings of Chubb et al. (1989), where they found out that a lower background contrast causes a higher transparency perception. Furthermore, I observed that the stimuli which seem strictly more transparent than the stimuli they are compared to, have strictly higher ratios. This shows that when there is transparency to be judged, the differences d between the ratios relate to the differences in the perceived transparencies of the compared stimuli. However, the differences between the ratios calculated with contrast metrics MC, SAM and SAW are relatively low, although the difference between the transparencies is high, in other words, one stimulus has strictly more transparency than the other. In such a case, I expected the difference between the ratios to be high and correlate with the difference between the perceived transparencies. The only contrast metric for which the difference between the ratios is high is $SAMLG$. This observation agrees with the findings of Aguilar and Maertens (2022), that $SAMLG$ predicts the difference of perceived transparencies.

As it turns out, the contrast metric $SAMLG$ predicts the difference of perceived transparency then there is a transparency to be judged, but can not predict when the transparent media is opaque, hence there is no transparency to be judged. As the goal of the paper is to find a contrast metric that can predict perceived transparency, it is more reasonable to study the stimuli where transparency can be seen. In doing so, I am allowed to state that the ratios calculated with contrast metric $SAMLG$ can be considered as the perceived transparency and that $SAMLG$ can predict the differences between the perceived transparency better than the other contrast metrics.

The same applies with the stimuli of Set A. I noticed that when there was a noticeable difference between the perceived transparencies, the differences between the ratios were higher than the differences when the media seem almost identical. However, it was not always the case that the ratios calculated with different contrast metrics predict the perceived transparency. When the luminance t is low (0.1), the ratios of the stimuli were higher than the stimuli they were compared to, even though they seemed less transparent. On the other hand, the differences d between the ratios correlate with the differences in perceived transparencies. This implies that although the ratios R can not be considered as the perceived transparency, the difference d between the ratios definitely correlates with the difference between the perceived transparency.

4.1 Limitation of Current Work

Without a doubt, I can say that using only stimuli from Set A and Set B created some issues, as most of the stimuli did not seem transparent or their ratios were higher than 1.0, which made the judgment challenging. A reason for that might be the choice of transmittance α. I observed with the first group of stimuli that high transmittance result in the contrast of the transparent medium being higher than the background contrast. Therefore, I end up using transmittance values equal lower than 0.5. However, using these transmittance values was also problematic with the stimuli of Set B, because in the end most of the stimuli seemed opaque due to low transmittance α. To solve this issue, for future work one might consider selecting transmittance α between 0.1 and 0.5 for Set A, and 0.5 and 0.9 for Set B. That way, the chance of having a background contrast lower than the contrast of the transparent medium, or the transparent medium appearing opaque might be reduced.

Another reason for this issue might be the choice of background contrast. As mentioned above, there were some cases with the stimuli of Set A, where the background contrast was lower than the contrast of the transparent medium. To prevent this, the choice of background contrast can be done as follows: instead of fixing a minimum background contrast for differing transmittance α and luminance t with an arbitrary decider value 0.1, the minimum background contrast could depend on the contrast of the transparent medium. Achieving this can be planned in two steps, 1) calculating the contrast of the transparent medium and calling it e.g. x, and then 2) regardless of the α and t, generating stimuli where the background contrast is at lowest x. In Figure 18, the steps are sketched. For example if the contrast of the transparent medium x from step 1) is 0.3, the background contrasts of the stimuli with the same transparent medium would vary between 1.0 and 0.3. Thus, the complication of background contrast being lower than the transparent medium contrast would be solved.

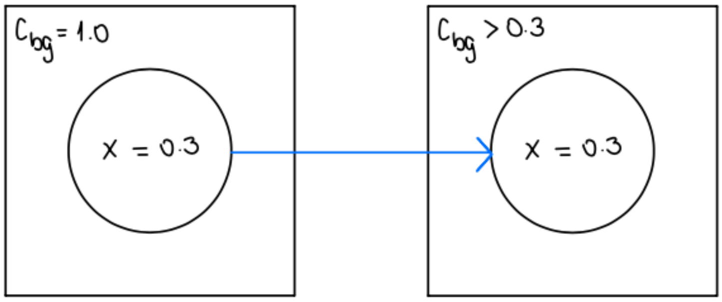


Figure 18: A sketch to explain how the choice of background contrast can be done in future work. On the left side a stimulus is rendered where the background has the highest contrast $c_{bg}(MC) = 1.0$ and the transparent medium has the contrast $c_{tm}(MC) = 0.3$. The transparent medium of the stimuli with the highest background contrast is cut out and pasted on another background. The right side shows that for every combination of α, t of the medium, the background contrast should always be higher than the contrast inside the transparent medium (0.3).

4.2 Relation to Previous Work

Robilotto and Zaidi (2004) found out that perceived transparency and perceived contrast are connected and that reducing background contrast decreases the perceived transparency of the medium. Contrarily, Chubb et al. (1989) observed that stimuli with lower background contrast appear to have a higher contrast than the stimuli with higher background contrast and therefore would appear more transparent.

Here, I tried to solve this contradiction and observed an interesting outcome. The observations I made with the stimuli of Set B correlate with the findings of Chubb et al. (1989), that with decreasing background contrast, the perceived transparency increases. On the other hand, there are two effects when I examined the stimuli of Set A. First, when luminance t is higher than 0.1, the effect agreed with Chubb et al. (1989)'s observations. Second, when the luminance t is low (0.1), the perceived transparency increases with increasing background contrast. This observation contradicts the previously mentioned findings and agrees with the findings of Robilotto and Zaidi (2004).

In my opinion, the observation made with low luminance t is an exception and assume that the reason for this confusion can be explained by the observation that a dark transparent medium seems more transparent than a light one for identical physical transmittance α. This effect was observed in previous work by Aguilar and Maertens (2022) and Singh and Anderson (2002)). Consequently, I believe it is the fact that the perceived transparency increases with decreasing background contrast, as Chubb et al. (1989) observed.

4.3 Open Questions

As I mentioned above, the collected data is not enough and might not be accurate. As I compared the stimuli with my subjective impression, I limited the luminance t to four, and transmittance α to three values. Therefore, I suggest for future researchers to conduct a study with multiple observers and the necessary technology to answer the research questions better.

I suggest that in future studies, more stimuli with additional luminance t and transmittance α should be explored. Conducting an experiment with more stimuli with varying t and α would bring out more information about the relations.

Furthermore, I used two backgrounds to cut out transparent media, and their contrasts were $c_{bg} = 1.0$ and $c_{bg} = 0.1$. Since they are both extremes, there were problems to be dealt with which resulted in having fewer stimuli than expected. I advise for future studies more backgrounds to be chosen from which the transparent media will be cut out.

5 Conclusion

I studied the effect of background contrast on the transparency perception by evaluating with my subjective impression. I also examined whether the ratio can be considered as the perceived transparency and the difference between the ratios as the difference between the perceived transparencies. I found out that for most of the stimuli, the stimuli with lower background contrast seem more transparent than the stimuli with higher background contrast. Furthermore, I observed that there is a relation between the difference of perceived transparencies and of the ratios. The difference of ratios increases when the difference between the perceived transparencies increases. In agreement with, I observed that the contrast metric *SAMLG* can predict the difference of perceived transparency better than the other compared contrast metrics: *MC*, *SAM*, and *SAW*.

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