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Bachelor Thesis

The Effect of Surround-Flicker induced Adaption on contrast sensitivity.

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Affidavit

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, 16.01.2024

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Abstract

There are multiple theories on the brightness representation of surfaces in the human visual system. One of those theories is *neural filling-in*. Robinson and de Sa (2012, 2013) conducted multiple experiments in which they probed these theories. For this they used two adaptation paradigms, flicker adaptation and surround flicker induced adaptation. In their latest work from 2013 they argued against the theory of *neural filling-in*. In the following bachelor thesis an experiment, in which the adaptation effects of flicker adaptation and surround flicker induced adaptation are compared, is proposed, conducted and discussed. The experiment was carried out as a pilot study. The results provide evidence against the argumentation of Robinson and de Sa (2013). They show the complications in comparing these two adaptation paradigms and the difference in the strength of the adaptation effect.

Zusammenfassung

Es gibt mehrere Theorien, welche die Helligkeitswahrnehmung von Flächen im Menschlichen Visuellen System betrachten. Eine von diesen Theorien ist *neural filling-in* (neuronales Ausfüllen). Um diese Theorien zu testen führten Robinson and de Sa (2012, 2013) mehrere Experimente durch. Dafür nutzen sie zwei Adaptionsparadigmen namens flicker adaptation (Adaption durch Flackern) und surround flicker induced adaptation (induzierte Adaption durch äußerliches Flackern). In ihrer Veröffentlichung von 2013 argumentierten sie gegen die *neural filling-in* Theorie. In der folgenden Abschlussarbeit wird ein Experiment, in dem die Adaptationseffekte von flicker adaptation und surround flicker induced adaptation verglichen werden, vorgeschlage, druchgeführt und ausgewertet. Das Experiment ist als Pilotstudie zu betrachten. Aufgrund der Resulat kann die Argumentation von Robinson and de Sa (2013) infrage gestellt werden. Sie zeigen die Herrausforderungen beim Vergleich der beiden Adaptionparadigmen und Unterschiede in der Stärke der Adaptionseffekte.

Contents

1 Introduction

In 2013 Robinson and de Sa published a paper called “Dynamic brightness induction causes flicker adaptation, but only along the edges: Evidence against the neural filling-in of brightness”. In this paper they studied the question whether perceived brightness in the human visual system is represented in a retinotopic map, that is filled in from the signals of cells for contrast edge detection (Robinson & de Sa, 2013). The question arises because there are multiple theories to explain how the brightness of a surface is represented in the brain. In this context luminance refers to the strength of the emitted light and brightness refers to how strongly we subjectively perceive it. In addition, retinotopic means that a neuron in the retinotopic map represents a specific neuron in the retina and neighboring neurons in the map also represent neighboring neurons in the retina.

1.1 Theories for Brightness Representation

Three of those theories for brightness representation in the brain are depicted in Figure 1. Each theory is applied to the same stimulus (Figure 1a). All theories have two stages, the retina and the post retinal representation. The active neurons are highlighted in red.

The first of those theories is *neural filling-in* (Robinson & de Sa, 2013). In this theory, cells for contrast edge detection in the retina propagate brightness information to their corresponding cells in a retinotopic map. Figure 1b shows these edge detection cells. Figure 1c shows the receiving edge cells in the retinotopic map. Here the brightness information of the interior is "filled-in" from those edge cells. That means brightness information of the interior is not directly transmitted from the retina. The information is only inferred from the edge signals. Both brightness information of the interior and the edges are explicitly represented in the retinotopic map.

The second theory is *symbolic filling-in* (Robinson & de Sa, 2013). In this theory only the information of the contrast edges is propagated from the retina. These edge detection cells are shown in Figure 1d. This is similar to *neural filling-in*. The difference is, that there is no

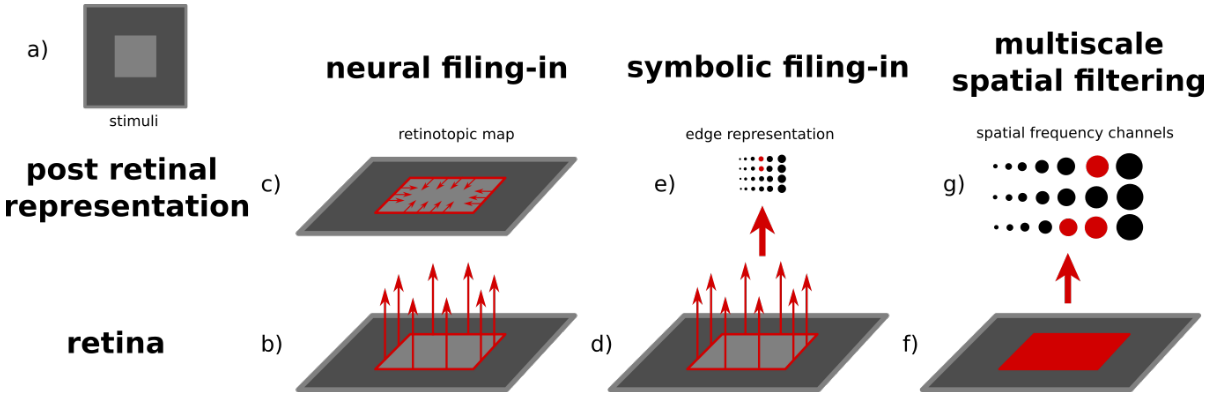

Figure 1: *Theories for brightness representation of a surface in the brain.* For each theory there is a depiction of the retina and the post retinal representation. Highlighted in red are the active cells for perceiving a stimulus (a). In neural filling-in the cells for contrast edge detection propagate their information (b) to their counterparts in the retinotopic map, where the cells representing the inside are filled in (c). In symbolic filling-in the cells for contrast edge detection also propagate their information to the post retinal representation (d) but here only the edges are represented non-retinotopicly and information about the interior is inferred (e). Lastly, according to the multiscale spatial filtering theory the brightness information (f) is represented in specific spatial frequency selective channels, wherein every channel is a group of neurons representing a specific spatial frequency (g).

retinotopic representation. Instead, only the information of the contrast edges is explicitly represented. A symbolic representation of this is shown in Figure 1e. Note that the active cells are non-retinotopic. Information about the interior is only "symbolically" filled in.

The third theory is *multiscale spatial filtering* (Robinson & de Sa, 2013). In this theory all brightness information of the surface is transmitted. This is shown in Figure 1f. Note that information of the edges and the interior is transmitted. This information is then represented in specific spatial frequency selective channels. Each channel is a group of neurons representing a specific spatial frequency. Therefore, there is no retinotopic representation but still an explicit representation. This is similar to the *symbolic filling-in* theory. A representation of these channels is shown in Figure 1g. Furthermore, all spatial frequencies that are present in an image are represented in the corresponding channel. This is unlike the *symbolic filling-in* theory, where only the high frequency channels, representing the edges, are active.

Robinson and de Sa (2013) discussed these different theories. They also performed experiments to test whether there is indeed evidence for the *neural filling-in* theory. In the following

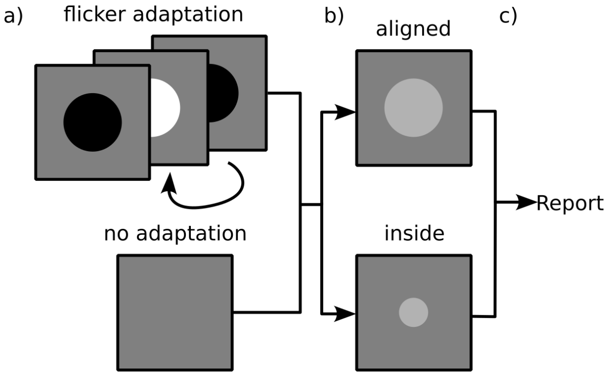

Figure 2: *Diagram of the temporal sequence in the flicker adaptation paradigm.* This is the paradigm used by Robinson and de Sa (2012). There were two sessions (a), one with an adaptation phase with flicker adaptation and one without an adaptation phase. In the next phase there were two conditions (b), one in which the test stimulus is aligned with the flicker stimulus and one in which the test stimulus is located inside the flicker stimulus. The last phase is the report phase where the subject reports their answer (c).

two studies by Robinson and de Sa (2012, 2013) will be describe in which they tried to test these different theories.

1.2 Flicker Adaptation

In their study Robinson and de Sa (2012) used an adaptation paradigm they called flicker adaptation. Adaptation paradigms consist of two phases, the adaptation phase, and the test phase. In flicker adaptation the observer first adapts to a flickering modulation. This adaptation phase is shown in Figure 2a. In the next phase the observer has to detect a test stimulus of low contrast. This test phase is shown in Figure 2b. The ability to detect a change in contrast in the adapted location is expected to be substantially impaired after adaptation.

The critical condition in Robinson and de Sa (2012) was the location of the test stimulus. The conditions were, aligned with or inside of the modulation. Both of these conditions are shown in Figure 2b. Robinson and de Sa (2012) measured at which contrast strengths the subjects could detect the test stimulus. Furthermore, there were two trials, one with and one without an adaptation phase. Both trials are shown in 2a.

The theories mentioned earlier would predict different results. *Neural filling-in* would predict that in both conditions the adaptation with flicker adaptation has a measurable effect on contrast detection. This is because in the aligned condition, neurons that are active during the test phase are identical to the adapted ones from the adaptation phase. And in the inside condition, neurons that are active are part of the neurons that were filled in in the adaptation phase, thus have been adapted. In comparison, *symbolic filling-in* and *multiscale spatial filtering* would predict an effect only in the aligned condition. This is because the neurons that are active in the test phase are identical to the ones that are adapted in the adaptation phase. The neurons that are active in the inside condition during the test phase are different from the adapted neurons thus there should be no effect. In *symbolic filling-in* theory that is because the edges are different. In *multiscale spatial filtering* theory that is because the spatial frequencies are different.

The result was that the contrast threshold was significantly higher in both adaptation conditions (Robinson & de Sa, 2012). But in the inside condition this difference was significantly smaller. Robinson and de Sa (2013) argued that this would speak for *neural filling-in* and against the current models of *symbolic filling-in* and *multiscale spatial filtering*.

1.3 Surround Flicker induced Adaptation

In their work from 2013, Robinson and de Sa used a different adaptation paradigm they called induction-derived flicker adaptation. Like with flicker adaptation, the observer first adapts to a flickering modulation, then has to detect a test stimulus. The difference lies within the modulation. Induction-derived flicker adaptation uses a phenomenon called brightness induction. One effect of brightness induction is shown in Figure 3. The medium gray inside square on the left is perceived lighter than the inside square on the right. This is because the same gray surface is perceived darker on a lighter background and lighter on a darker background. When looking at a surface the brightness depends on the luminance of the surrounding. In induction-derived flicker adaptation the modulation is not a flickering shape but instead a flickering background. But through brightness induction it seems as if the inner surface is also modulated. Like during flicker adaptation, the ability to detect a change in contrast in the adapted location is expected to be substantially impaired. Contrary to

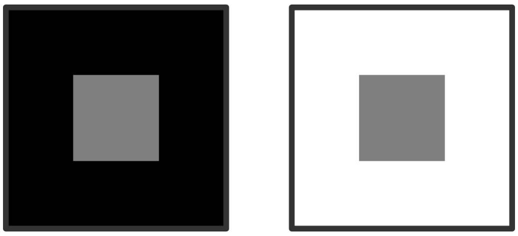

Figure 3: *Brightness Induction.* One effect of brightness induction is that the left inner square appears lighter than the right inner square. This is because we perceive the same gray luminance lighter on a darker background and darker on a lighter background.

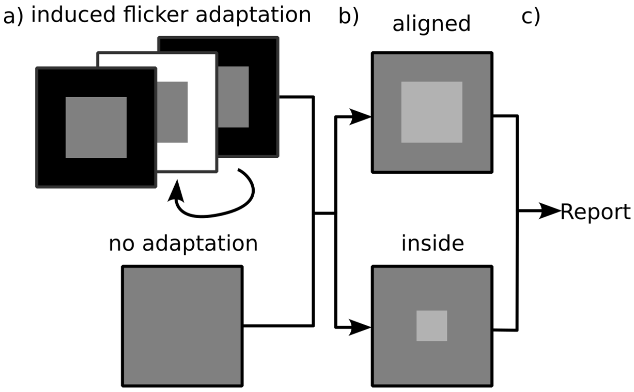

Figure 4: *Diagram of the temporal sequence in the surround flicker induced adaptation paradigm.* This is the paradigm used by Robinson and de Sa (2013). Similar to Robinson and de Sa (2012) there are two session (a), with and without an adaptation phase, two conditions (b), inside and aligned, and a report phase (c). The difference is the flicker type. Due to this modulation being surround flicker induced adaptation, only the background is flickering.

Robinson and de Sa (2013), in this work this phenomenon will be called surround flicker induced adaptation. This is to emphasize that only the surrounding area is flickering, and the inner modulation only appears through brightness induction.

The procedure was similar to the procedure from Robinson and de Sa (2012). In the study by Robinson and de Sa (2013) there were two trials, one with an adaptation phase and one without. This is shown in Figure 4a. Note that in the adaptation phase, in contrast to flicker adaptation, only the outside is flickering. After this the test phase is conducted, during which the observer is presented with a low contrast test stimulus. For both trials the critical condition is the location of this test stimulus, that is inside of or aligned with the inner adaptation square. Both conditions are shown in Figure 4b. Robinson and de Sa (2013) measured at which contrast strengths the subjects could detect the test stimulus.

Similar to the above reasoning (Section 1.2) *neural filling-in* would predict that in both conditions the adaptation to surround flicker induced adaptation has a measurable effect on contrast detection. *Symbolic filling-in* and *multiscale spatial filtering* would predict only an effect in the aligned condition.

The results were that the contrast threshold was significantly higher, only in the adaptation trial in the aligned condition. The adaptation had no effect in the inside condition. To eliminate unwanted influences, they repeated the experiment two times and changed multiple parts each time. They checked for influences from the detection task, size of the stimuli, location of the inner and outer edges of the inducing region, and frequency of the flicker. None of the results differed significantly from the first trial (Robinson & de Sa, 2013).

There is another possible explanation as to why there was no significant threshold difference with the inside condition. The induction effect is just not strong enough to induce a significant adaptation effect. In the experiment by Robinson and de Sa from 2012 the threshold difference was very small. So, to be able to provoke a similar result it seems reasonable that the adaptation effect of surround flicker induced adaptation has to be as strong as the adaptation effect of flicker adaptation. My work will address this problem by trying to validate the induction strength of surround flicker induced adaptation and discussing implications of the findings arising from this.

1.4 This Work

One possibility is to find values for flicker adaptation and surround flicker induced adaptation, so that the perceived flicker modulation of the center is nearly identical. As such an experiment is proposed and was conducted where the participants were shown both flicker adaptation and surround flicker induced adaptation side by side. The luminance values for surround flicker induced adaptation were fixed and the participant had to adjust the luminance values of flicker adaptation. The task was to match the inside brightness of surround flicker induced adaptation and flicker adaptation. During the preparation for this experiment multiple problems arose, complicating the execution of the study. These complications will be discussed in detail in Section 3.2. As a result, the experiment was only conducted as a pilot study. The procedure of this pilot study will be discussed in Chapter 2 and the results and observations in Chapter 3.

It is worth mentioning that De Valois et al. (1986) did a similar study to the one proposed in this work. Although the procedure of their study was almost the same, their research question was quite different. They looked for the relation between different flicker frequencies and contrast matching of flicker adaptation and surround flicker induced adaptation. And in a second study they researched the phase shift between flicker adaptation and surround flicker induced adaptation. Furthermore, they used a sinusoidal wave for the flicker whereas the proposed experiment used a square wave. Although, their experiments differ in multiple ways from mine, their results are useful for comparison.

The result from the first study would be a pair of luminance values, for which surround flicker induced adaptation and flicker adaptation are comparable. In case these values differ from the ones originally used by Robinson and de Sa (2012, 2013), it was planned to do two other experiments. They will be discussed in detail in Section 4.3. It was planned to do a second experiment in which the adaptation effect of flicker adaptation would tried to be confirmed in both the inside and aligned condition. And a third experiment where the adaptation effect of surround flicker induced adaptationwould tried to be confirmed, again in both the inside and aligned condition.

There are multiple possible results that could be expected from those three experiments. Each of these results would have different implications for the theories about brightness representation (Section 1.1).

The first result could be that it is not possible to find values for which flicker adaptation and surround flicker induced adaptation are comparable. The results of this work suggest otherwise. Another possible result could be, that such values can be found, but with those values the adaptation effect of flicker adaptation is not strong enough in the inside condition. Both cases would suggest that the argumentation from Robinson and de Sa (2013) against *neural filling-in* is not applicable. It is not possible to have surround flicker induced adaptation luminance values for which the adaptation intensity can be verified. Thus surround flicker induced adaptation could just be to weak to cause an adaptation effect for the inside test surface. Either way, both results would be consistent with the theories of *symbolic filling-in* and *multiscale spatial filtering*. Both theories assume that the adapted neurons are different from the ones representing the inside test surface.

Another result could be that under comparable luminance values, surround flicker induced adaptation still only causes an adaptation effect in the aligned condition but not in the inside condition. This result would be according to the theories of *symbolic filling-in* and *multiscale spatial filtering*. Again, both theories assume the adapted neurons are different from the ones representing the inside test surface. It would be contradictory to the theory of *neural filling-in*. The theory assumes neurons representing the inside test surface are being filled in and thus should also be adapted. The result would be the same as in the study by Robinson and de Sa (2013). Thus, it would strengthen their argumentation against *neural filling-in*.

However, there is also the possibility that surround flicker induced adaptation now causes an adaptation effect in both conditions. This result would support *neural filling-in* and oppose *symbolic filling-in* and *multiscale spatial filtering*. It would furthermore speak against the argumentation in Robinson and de Sa (2013) for those two theories.

2 Methods

In this experiment the comparability of flicker adaptation and surround flicker induced adaptation will be researched. For this, both flicker paradigms are shown side by side. The task is to adjust the flicker adaptation luminance so that the perceived brightness of the inside squares match. The result would be comparable luminance values for flicker adaptation and surround flicker induced adaptation for which subjects matched the flicker modulation.

During preparations for this experiment multiple complications arose. Both flicker modulations seemed to be out of phase, the task was not feasible for the whole luminance range, and proved to be quite difficult for the subject. These problems will be discussed in Section 3.2 and solutions will be proposed in Section 4.2. For these reasons this study only was conducted as a pilot study.

2.1 Subjects

Due to the fact that this study is a pilot study only the author participated in the experiment.

2.2 Apparatus

Stimuli were displayed on a 24-in VIEWPixx/3D LCD monitor (1,920 x 1,080 px, 120 Hz) (VPixx Technologies Inc., Saint Bruno, QC, Canada). Luminance output was within a range of 0-102 cd/m^2 at a 16-bit resolution. Luminance verification was conducted with a Minolta LS-100 photometer (Konica Minolta, Tokyo, Japan). A five-button ResponsePixx response box (VPixx Technologies Inc., Saint Bruno, QC, Canada) was used as the response input device (Figure 6). By pressing the left, right, upper, and lower button the luminance of the flicker adaptation modulation was changed. By pressing the middle button, the adjustment was confirmed. Stimuli were generated with Python 3 using the HRL module (http://github.com/computational-psychology/hrl). A chinrest was used for a fixed viewing distance of 100 cm. Furthermore, the experiment was conducted in a dark room in a quiet environment.

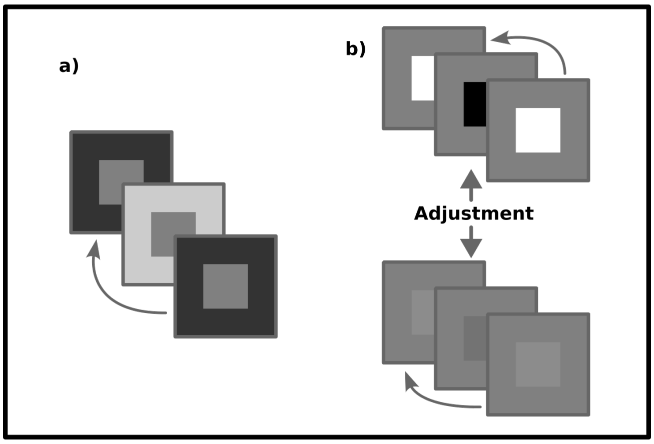

Figure 5: *Representation of the stimuli.* This Figure shows a representation of the shown stimuli. Left (a) is the surround flicker induced adaptation modulation cycling through the two luminances, light and dark. The contrast value for this modulation is fixed. On the right (b) the flicker adaptation modulation is shown, also cycling through the two luminances. The flicker adaptation contrast value is not fixed, but has to be adjusted by the subject. The upper cycle represents a high contrast value and the lower cycle a low contrast. The modulation arrangement, which one is left and right, is random. This figure is one of these two arrangements.

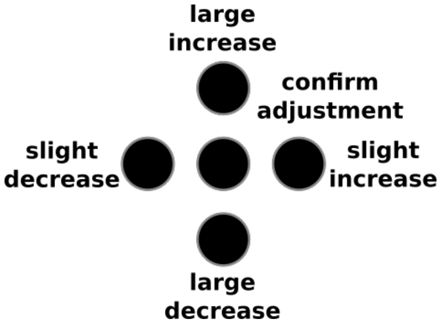

Figure 6: *Response buttons.* This figure shows the arrangement of the five response buttons. The upper and lower buttons change the contrast value by 0.025, the upper button increasing it and the lower button decreasing it. The left and right buttons change the contrast value by 0.0025, the right button increasing it and the left button decreasing it. A press of the middle button confirms the contrast adjustment.

2.3 Stimuli

The stimuli were composed of both flicker modulations, flicker adaptation and surround flicker induced adaptation, on a gray background (50,4 cd/m^2). A representation of this is shown in Figure 5. Each flicker is composed of two luminance stimuli, one with a high and one with a low luminance value. Figure 5a shows the surround flicker induced adaptation modulation cycling through two luminance stimuli. Figure 5b shows the flicker adaptation modulation also cycling through two luminance stimuli. While the surround flicker induced adaptation had fixed luminance values depending on the trial, the flicker adaptation luminance values were adjustable by the subject.

Luminance measurement suggested that the monitor was not homogeneous. Because of this the flicker composition, which modulation is either left or right, was randomized with a 50% chance.

In a luminance verification 1.1 cd/m^2 was measured as the standard error for the displayed luminance.

Both flickers were modulated by a fixed 3.3 Hz square wave (150 ms per frame). The frequency was chosen to match the 153 ms from the Robinson and de Sa (2013) experiment and the 120 Hz frame rate of the monitor used.

Both flicker adaptation and surround flicker induced adaptation have two luminance values, one for the dark and one for the light part of the flicker. Both luminance values oscillate with the same distance around the medial value 50,4 cd/m^2. These two values can be described as a contrast value with:

$$\text{contrast} = \frac{\text{distance to medial value}}{\text{medial value}}$$

This means a modulation with a contrast of 0.2 is composed of a low luminance stimulus with 40,32 cd/m^{2}and a high luminance stimulus with 60,48 cd/m^2.

To match the values from the Robinson and de Sa (2013) experiment starting values in the range of 0 cd/m^2 to 100,8 cd/m^2 with a medial value of 50,4 cd/m^{2}were chosen. However, previous pilot trials suggested that high contrast, i.e. luminance values close to 0 cd/m^2 and 100,8 cd/m^2 made it impossible to carry out the task. This will be explained in detail in Section 2.4. For now, this means only contrast values up to 0.4 were used. Thus the values were still in the same range and have the same medial value as the Robinson and de Sa (2013) experiment, but only work with smaller values within this range.

Both flicker adaptation and surround flicker induced adaptation had the same stimulus size. The outer squares had a size of 10 cpd and the inner squares a size of 4 cpd. Thus, both modulations individually match the stimulus size from the Robinson and de Sa (2013) experiment. The distance between both modulations was 1.6 cpd.

During the experiment the flicker adaptation outer square and the background were indistinguishable from another. This was not fixable without changing the background color. But changing it would probably have interfered with the perceived brightness of the modulations, especially for surround flicker induced adaptation.

Another complication in earlier pilot trials was that the modulations for surround flicker induced adaptation and flicker adaptation appeared to be out of phase. This complication will be discussed in detail in Section 3.2. In an attempt to resolve this, the flicker adaptation modulation was delayed by two frames i.e. 16.7 ms. Further pilot trials suggested this was the best amount for the author as a subject. This delay is shown in Figure 7. The flicker adaptation modulation always switched the luminance type two frames after the surround flicker induced adaptation modulation switches the luminance type. The Figure 7 will be discussed in detail in the next section.

2.4 Procedure

The experiment consisted of five blocks with six trials each. Each block had the same set of six fixed contrast values for surround flicker induced adaptation, which were shown in randomized order. Each block had a different starting contrast for flicker adaptation. All trials in one block had the same flicker adaptation starting value. The order of the blocks was also randomized. At the start of each trial, the stimuli were shown after a delay of one second with a blank gray screen (50.4 cd/m^2).

As Stevens (1970) reported, the sensation of brightness grows with a fractal power function in proportion to the stimulus. The flicker adaptation and surround flicker induced adaptation contrast values were chosen accordingly. The surround flicker induced adaptation test values were (0.01, 0.02, 0.04, 0.08, 0.16, 0.32). The flicker adaptation starting values were (0.01, 0.03, 0.06, 0.12, 0.24).

The task was to change the flicker adaptation contrast so that the flicker adaptation modulation matches the surround flicker induced adaptation inside modulation. This is shown in Figure 5. It was important that only the surround flicker induced adaptation inside modulation was minded, not the outside modulation.

Given the task was very difficult there was no time limit to ensure a precise adjustment.

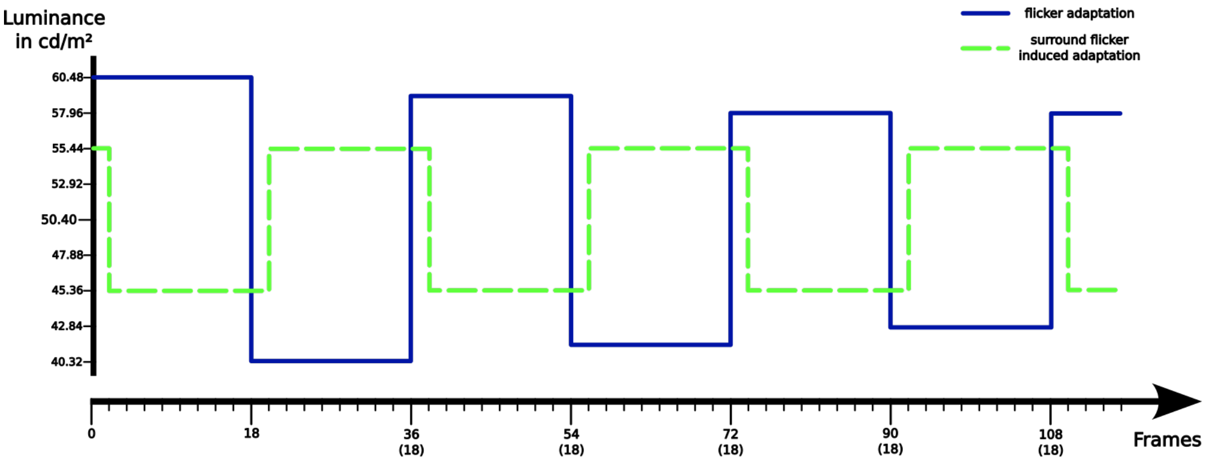

Figure 7: *Luminance of the flicker adaptation and surround flicker induced adaptation modulations during a trial.* This figure shows a possible luminance modulation of the stimuli during a fictional trial. The x-axis shows the time in frames, highlighting a full cycle of 18 frames. The y-axis shows the luminance in cd/m^{2}and the medial luminance value of 50.4 cd/m^2. The solid blue line shows the flicker adaptation square modulation. In this figure the surround flicker induced adaptation modulation starts at a contrast value of 0.2, it is alternating between 40.32 cd/m^2 and 60.48 cd/m^2. Two times after a full cycle the contrast value is reduced by 0.025. The dashed green line shows the surround flicker induced adaptation square modulation. In this figure the flicker adaptation modulation has a fixed contrast value of 0.1. This means the modulation alternates between 45.36 cd/m^2 and 55.44 cd/m^2. The flicker adaptation cycle is delayed by two frames, always switching brightness two frames after the surround flicker induced adaptation modulation does. Both modulation cycles are reversed from each other.

The flicker adaptation contrast value could be changed by pressing one of the four outer buttons. This is depicted in Figure 6. The upper and lower buttons imposed a strong change on the flicker adaptation contrast value, i.e. 0.025, with the upper button increasing it and the lower button decreasing it. The left and right buttons imposed a weak change on the flicker adaptation contrast value, i.e. 0.0025, with the right button increasing it and the left button decreasing it. By pressing the middle button, the adjustment was confirmed and the trial closed.

Figure 7 depicts the luminance profile of a hypothetical experiment. The x-axis marks the time in frames and the y-axis represents the luminance in cd/m^2. The graph of the flicker adaptation luminance is a green dashed line and the graph of the surround flicker induced adaptation luminance is a blue solid line. Both flicker types have a square wave modulation and alternate between two luminance values. The high and low luminance values have the same distance to the medial of 50.4 cd/m^2. Each cycle is 18 frames. The flicker adaptation cycle is delayed by two frames as mentioned in the previous chapter. After one full cycle the contrast of the flicker adaptation modulation is reduced by 0.025. This happens twice. Thus simulating the pressing of the large decrease button two times. The contrast value of the surround flicker induced adaptation modulation is fixed and does not change. Both modulation cycles are reversed from each other. While the flicker adaptation shows the low luminance, the surround flicker induced adaptation shows the high luminance and vice versa. This accommodates for the reversed brightness in brightness induction. As explained in Section 1.3, in surround flicker induced adaptation the inside brightness is the opposite of the outside brightness.

When the outside modulation has a higher luminance the inside brightness is perceived darker. If the outside modulation has a lower luminance the inside brightness is perceived lighter.

Earlier pilot trials suggested that carrying out the experiment task with high contrast values was very hard. When the surround flicker induced adaptation modulation had a high contrast value, matching the inside modulation to the flicker adaptation modulation was very difficult. For one because the subject is distracted by the intense flickering. Furthermore the subject cannot discern if the contrast is very low or very high. This will be discussed further in Section 3.2. For the author contrast values below 0.4 were acceptable for the task. This was used as a threshold for the values for both surround flicker induced adaptation and flicker adaptation.

3 Results

3.1 Pilot Results

The results of the pilot study are displayed in Figure 8. The surround flicker induced adaptation test contrast values are marked on the x-axis. The subject adjusted flicker adaptation contrast values are shown on the y-axis. The grey dots represent trials. There are five grey dots per surround flicker induced adaptation test value. The blue points represent the mean per surround flicker induced adaptation test value. The blue bars represent the standard error.

The pilot study had three noticeable results.

Firstly, the surround flicker induced adaptation values increase with the flicker adaptation values. This means that higher surround flicker induced adaptation values correspond to stronger flicker intensity, up to the highest tested value at 0.32.

Secondly that although, higher surround flicker induced adaptation values correspond to higher flicker adaptation values, the increase of the flicker adaptation values is significantly smaller. This implies the intensity of the surround flicker induced adaptation modulation is significantly weaker than the intensity of the flicker adaptation modulation.

Lastly, higher surround flicker induced adaptation test values lead to a larger standard error. Low surround flicker induced adaptation test values have almost no error at all. Higher test values have a higher error. This is in line with two observations. First, the higher the test value the harder the task gets. Secondly, at higher test values small adjustments to contrast mattered less. Both of these observations will be discussed in the following section (3.2).

All these results were gathered in this pilot study. They must be verified in a larger study.

3.2 Observations

During the preparation of, and while participating in the study, the author made multiple observations regarding the experiment. Some of them were already talked about in Chapter 2 because they were observed early on and were included in the design of the study. These

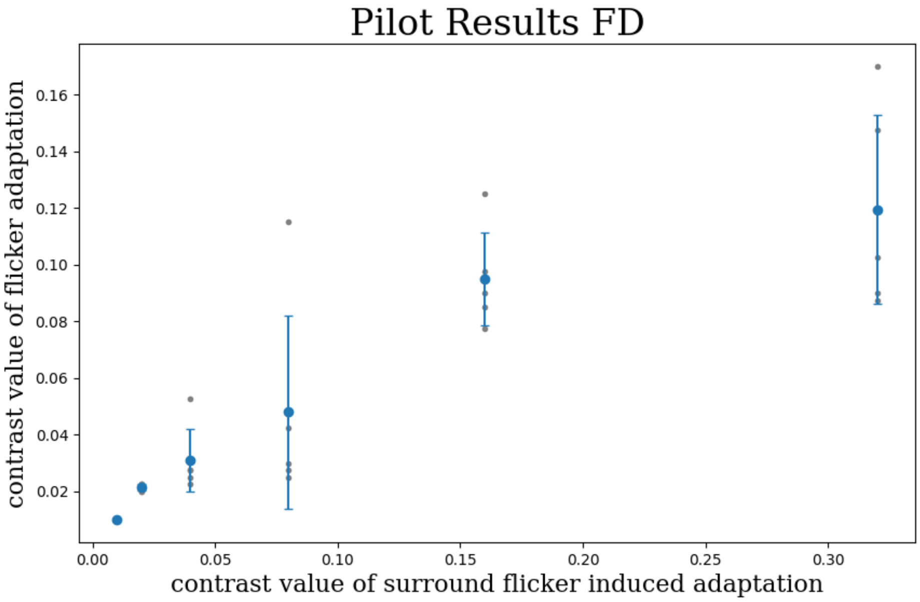

Figure 8: *Results of the pilot study.* This figure shows the results for the subject, that is the author. On the x-axis are the contrast values for the surround flicker induced adaptation modulation. On the y-axis are the contrast values for the flicker adaptation modulation. The gray dots represent the result of each trial. The large blue dots represent the mean for each surround flicker induced adaptation test value. The test values were (0.01, 0.02, 0.04, 0.08, 0.16, 0.3). The blue bars represent the standard error.

phenomena complicated the study and hampered the adjustment task. In Section 4.2 it will be talked about specific solutions for some of these phenomena.

The first observation was, that the flicker adaptation and the surround flicker induced adaptation modulation seemed to be out of phase. The subject perceives the surround flicker induced adaptation inside modulation and the flicker adaptation modulation to be asynchronous. This occurs, despite the luminance of both modulation switching at the same time.

There are multiple studies debating if brightness takes time to be perceived (Blakeslee & McCourt, 2008; De Valois et al., 1986; Rossi & Paradiso, 1996). Rossi and Paradiso (1996) argued that brightness induction is a rather slow process (<5 Hz). Contrary Blakeslee and McCourt (2008) argued that brightness induction is nearly instantaneous (<24 Hz) and happens almost simultaneously with the perception of the inducer.

If brightness induction does indeed take time, it could be an explanation for this phenomenon. Because I observed this early on, I conducted some pilot studies where the flicker adaptation modulation was delayed by multiple frames. Finding and deciding on the right amount of delay proved do be very difficult. In the end two frames were chosen as the delay amount for this pilot study, as mentioned in Section 2.3. Also, the pilot study suggested that the right amount of delay might be different depending on the contrast value and the individual subject. This is in line with the findings by De Valois et al. (1986) that a phase lag probably exists but is hard to quantify. Still, I would propose a preparation study where subjects have to adjust the contrast value of flicker adaptation and also have to adjust the amount of delay. This will be further discussed in Section 4.2.

The second observation I made was that the difficulty of the task depended on the contrast value. The flicker adaptation adjustment was very hard for higher surround flicker induced adaptation contrast values. But it was relatively easy for low contrast values. At high surround flicker induced adaptation values the outside flicker was so intense that it was very difficult to observe the inside flicker. De Valois et al. (1986) describe a similar issue. According to their study the subjects had two contrary observations. One Observation was that the surround flicker induced adaptation modulation looked like there was a very pronounced flicker at the edges. The other observation was that it looked as if the center did not change in brightness at all. They observed this only at frequencies higher than 2.5 Hz. I noticed it at the frequency of 3.3 but only at higher contrast values.

For this reason there was a constraint on the contrast value as mentioned in Section 2.4 (0.4). I chose 0.32 as the highest surround flicker induced adaptation contrast value because in previous pilot studies the adjustment task was hard for me but still possible. This may be the reason for the high standard error in trials with a higher surround flicker induced adaptation contrast value (Figure 8) as stated in the previous section.

The third observation was that the need of accuracy in the adjustment task depended on the surround flicker induced adaptation test value. In trials with a low test value a precise adjustment was only possible by using the buttons for small increase or decrease. For low flicker adaptation contrast values, one small step in the contrast value made a visible difference for the observer. For high test values it was the opposite. Doing the adjustment task was possible without using the buttons for small increase/decrease. One small step for the flicker adaptation contrast made almost no visible difference. Thus at low flicker adaptation contrast values small increases/decreases are necessary, but at high contrast values they make no visible change. This strained the subject of the pilot study, increasing the difficulty of the task. It might also have lead to a higher error in the responses.

The last group of phenomena I observed were connected to the visual focus of the participant in relation to the stimulus during the study. First, I observed that the surround flicker induced adaptation inside modulation appeared to be stronger when it was in the visual periphery. When looking directly at the surround flicker induced adaptation inside the modulation appeared weaker if at all.

Secondly, I observed that when looking at the same position for a significant amount of time, the edges of the flicker disappeared. This applies to both flicker adaptation and surround flicker induced adaptation. This is likely because of the effect of the adaptation paradigm. Both of the last phenomena show the difficulty in executing the adjustment task.

4 Discussion

The findings of this pilot study suggest the quantification of the intensity relation between flicker adaptation modulation and surround flicker induced adaptation modulation is difficult. In this pilot study it could only be achieved for a surround flicker induced adaptation contrast of 0.32 . At high contrast values the quantification was not possible.

4.1 Implications

First it needs to be emphasized that this study is only a pilot study. All implications need to be verified. Even though this is a pilot study there are some conclusions that can be made. And for verification we can look at the study by De Valois et al. (1986) and compare the results.

Robinson and de Sa (2012) showed that cells which respond to physical modulation of luminance within a uniform region can be adapted by flicker adaptation. Furthermore, Robinson and de Sa (2013) showed that these specific cells cannot be adapted by surround flicker induced adaptation. They concluded that this speaks against a filled in retinotopic map and thus against the theory of *neural filling-in*. To make this conclusion it has to be assumed that surround flicker induced adaptation provokes a strong enough adaptation. Only if surround flicker induced adaptation provokes a strong enough effect and is still incapable of inducing adaptation of the cells representing the inside, the conclusion can be made that there is no retinotopic representation. However, Robinson and de Sa (2012) showed that flicker adaptation was capable of causing an adaptation effect. By assuming the adaptation effect of flicker adaptation and surround flicker induced adaptation are comparable, they also assumed that the surround flicker induced adaptation effect is strong enough.

As described in Section 3.1, the results suggest that the surround flicker induced adaptation intensity is weaker than the flicker adaptation intensity. Furthermore, Section 3.2 discussed multiple aspects that showed the difficulty comparing the intensity of flicker adaptation and surround flicker induced adaptation.

This is supported by De Valois et al. (1986). One of their conclusions was that surround flicker induced adaptation produces a third to half as much brightness as flicker adaptation. They tested this for two surround flicker induced adaptation contrast values. They also reported difficulty in matching the modulations at high frequencies (≥ 2.5 Hz). As my study was conducted with a fixed frequency of 3.3 Hz, all trials should be affected by this. However, this was only observable at higher contrast values. Nevertheless, this still shows the difficulty in matching surround flicker induced adaptation and flicker adaptation.

As described in Section 3.2 and is mentioned by De Valois et al. (1986), in these high frequency or high contrast modulations, the observation of the surround flicker induced adaptation inside modulation is very difficult. Although the edges seem to flicker, the inside appears to be static. Blakeslee and McCourt (2008) argued that any effect in the induced region of surround flicker induced adaptation has to be the result of brightness induction. Thus, even if the center appears static and only the edges of the induced region appear to flicker, some form of brightness induction has to be present. However, it is important to note that in these cases the induction strength cannot be verified.

It can be argue that the difficulty in comparing flicker adaptation to surround flicker induced adaptation undermines the assumption that flicker adaptation and surround flicker induced adaptation are comparable. Furthermore, the results suggest that the adaptation effect of surround flicker induced adaptation is weaker than flicker adaptation. This weakens the assumption, that surround flicker induced adaptation has a strong adaptation effect. It is not verified that surround flicker induced adaptation is strong enough to provoke an adaptation effect for the cells representing the inside surface. This questions the assumptions by Robinson and de Sa (2013) made for their argumentation against *neural filling-in*. Naturally this does not prove *filling-in*, it only questions the argumentation for its disproof.

4.2 Solutions

Many aspects of the study made the task and thus the whole study more difficult. These complications were described in Section 3.2. In the following possible solutions will be discussed.

The first complication described was that both flicker modulations seemed out of phase. It appears that flicker adaptation and surround flicker induced adaptation do not change their brightness at the same time. In this pilot study a delay of two frames was added to the flicker adaptation modulation to reduce this effect, but it still appeared. De Valois et al. (1986) researched this phase shift in one of their studies. They argued for such a phase shift between flicker adaptation and surround flicker induced adaptation, but could not quantify it. They argued that the data was too variable to allow a precise quantification.

Earlier pilot studies suggest that this phase shift might be dependent on the contrast of the flicker and the individual observer. To solve this issue a preparation study for the experiment conducted in this pilot study would be appropriate. The aim would be to find the right amount of phase shift for the individual participant depending on the contrast value. This phase shift would be the amount of frames that flicker adaptation or surround flicker induced adaptation is delayed when viewed side by side.

The design would be similar to this study with a slight change to the task. Instead of only adjusting the flicker adaptation contrast value, an adjustment of the phase shift would also be possible. While trying to match the brightness of both modulations, the subject also has to adjust the phase shift to match both modulations. Naturally with fewer trials than this pilot study and with a focus on the phase shift. Both adjustments would be done by pressing a button on the five-button interface, e.g. up and down changing the luminance and left and right changing the phase shift. Depending on the results of this preparation study, changes should be made to the study conducted in this work. If the phase shift is subject dependent, the phase shift can be individually adjusted. If the phase shift is contrast value dependent then each surround flicker induced adaptation test value setting could have a different phase shift.

The second complication was, that at high surround flicker induced adaptation contrast values the adjustment task was not possible. Thus this study had a contrast threshold of 0.4. There are no immediate solutions to this. But earlier pilot studies suggested that the adjustment task was easier at lower frequencies. This is supported by De Valois et al. (1986). They stated that the adjustment task was easier at frequencies less than 2.5 Hz. A frequency of 1 Hz would be a natural candidate. Robinson and de Sa (2013) already used this frequency in one variation of their experiment. This variation produced the same result as the main experiment with 3.3 Hz. Even though, at a lower frequency the adjustment task might be possible for modulations with higher contrast values.

The third problem was that the appropriate contrast increase/decrease size depended on the flicker adaptation value. As stated in Section 2.4, sensation of brightness grows with a fractal power function. The surround flicker induced adaptation and flicker adaptation values were chosen accordingly. Contrary the contrast step sizes increase linear. The step sizes could be changed to be in line with the growth of the brightness sensation.

Although eventually reducing the strain on the subject, it complicates the design of this study. This has to be kept in mind.

4.3 Future Work

As already emphasized at the beginning of the last chapter, this study was conducted as a pilot study. Before running this experiment properly it would be reasonable to conduct the preparation study as described in Section 4.2. The information gained about phase shift should have implications on the future design of the study, proposed in this work. After finishing the preparation study, the study described in Chapter 2 should be carried out properly. By doing this we gain the highest comparable surround flicker induced adaptation contrast value and the corresponding adjusted flicker adaptation contrast value. If these values differ from the contrast values originally used, the experiment by Robinson and de Sa (2012, 2013) should be conducted again but with the comparable contrast values.

The design of the Robinson and de Sa (2012) adapted experiment would be similar to the original, as explained in Section 1.2. During each trial the subject has to adapt to flicker adaptation. After the adaptation the subject has to perform a detection task, with a low contrast test stimulus. In their study Robinson and de Sa (2012) used 2.3 cd/m^2 as the lower and 130 cd/m^2 as the higher value for the flicker. For this new experiment we use the previously mentioned flicker adaptation contrast value from the highest comparable contrast value pair. The critical condition would be whether the test stimulus is aligned with or inside of the flicker adaptation stimulus.

The next possible step would be to run the Robinson and de Sa (2013) adapted experiment, as explained in Section 1.3. The design of this next study would also be similar. The subject first adapts to surround flicker induced adaptationand then has to perform a detection task. In the original study by Robinson and de Sa (2013) they used 0 cd/m^2 as the lower and 102 cd/m^2 as the higher value for the flicker. Similarly to the previous experiment the surround flicker induced adaptation contrast value from the highest comparable contrast value pair is used. Again, the critical condition would be whether the test stimulus is aligned with or inside of the flicker adaptation stimulus.

If the pair of comparable contrast values for flicker adaptation and surround flicker induced adaptation can be found, then there are three possible scenarios. As this pilot study has shown, finding such a pair is difficult, but it also suggests that it is possible. The highest contrast value pair this pilot study found was 0.12 for flicker adaptation and 0.32 for surround flicker induced adaptation.

The first scenario is that an altered version of the experiment by Robinson and de Sa (2012) causes no adaptation in the cells representing the inside of the modulated region. For the highest comparable contrast value pair flicker adaptation is too weak to provoke adaptation. This suggests that surround flicker induced adaptation is also too weak to provoke adaptation in cells representing the inside of the modulated region. This would undermine the argumentation of Robinson and de Sa (2013) against *neural filling-in*. The reason why surround flicker induced adaptation has no adaptation effect on the inside cells is, that surround flicker induced adaptation may be too weak to provoke an adaption effect at all.

The second scenario is that an altered version of the flicker adaptation experiment by Robinson and de Sa (2012) causes adaptation in the cells representing the inside of the modulated region and an altered version of the surround flicker induced adaptation experiment by Robinson and de Sa (2013) causes no adaptation in the inside cells. Now the adaptation strength of surround flicker induced adaptation is verified and comparable to flicker adaptation. But surround flicker induced adaptation still provokes no adaptation effect for the inside cells. This would support the argumentation of Robinson and de Sa (2013) against *filling-in*. If a retinotopic map that is being filled in exists, cells representing the inside should also adapt to surround flicker induced adaptation. If this is not the case *neural filling-in* does not seem viable. This result would be in line with the theories of *symbolic filling-in* and *multiscale spatial filtering*. The inside cells are different from the cells representing the edges and thus should not be adapted.

The third scenario is, that in both altered experiments the modulation causes an adaptation in cells representing the inside of the modulated region. In the original experiments Robinson and de Sa (2012, 2013) used high contrast values for both their modulations. My study suggests that for comparable contrast values between flicker adaptation and surround flicker induced adaptation, the surround flicker induced adaptation value is always lower. This means that for a pair of contrast values the surround flicker induced adaptation value should be lower than the surround flicker induced adaptation value used in the original experiment. Still, it might be possible that only a lower value causes an adaptation effect for the inside cells. In pilot studies for surround flicker induced adaptation the inside flicker appeared to be stronger for lower contrast values. Either way this scenario would undermine the argumentation by Robinson and de Sa (2013) against *neural filling-in*. Instead the result would be in line with *neural filling-in*. Because the inside cells have also adapted, this supports the existence of a filled in retinotopic map. This result would speak against *symbolic filling-in* and *multiscale spatial filtering*. In both theories the cells that adapted during the flicker are different from the ones representing the inside. Thus, the inside cells should not have been adapted.

4.4 Conclusion

In their work Robinson and de Sa (2013) made a strong case against the theory of *neural filling-in*. They argued against the theory that the brightness of a surface is represented as a retinotopic map. Instead, they argued for the theories of *symbolic filling-in* and *multiscale spatial filtering*. In both theories brightness is represented differently but in neither of them in the form of a retinotopic map.

They based this argumentation on experiments they conducted with adaptation paradigms, i.e. flicker adaptation and surround flicker induced adaptation. Their results led them to suggest that surround flicker induced adaptation does not cause adaptation in cells representing the brightness inside of a surface. If these cells are part of a retinotopic representation, they should have been filled in during the adaptation phase. Thus they should have been adapted. Because that was not the case, Robinson and de Sa (2013) argued against such a retinotopic representation. But for this they had to assume that the adaptation effect of surround flicker induced adaptation is strong enough to provoke adaptation in such a potential retinotopic map.

This work tried to validate this adaptation strength by comparing it to the other adaptation paradigm, flicker adaptation. This comparison proved to be rather difficult for several reasons. Both modulations appeared to be out of phase when viewed side by side. A possible solution might be delaying one modulation by a few frames however, this has to be tested. A possible study for this was proposed in Section 4.2. Another complication was that the adjustment task was only possible for low contrast values. At high contrast values there was a dissonance in the perception of the modulation. It seemed to be that the edge region showed a very strong modulation. At the same time the center brightness appeared unchanged, as reported by De Valois et al. (1986). Although this dissonance in perception might be eased by a lower modulation frequency, there is no other clear solution.

The experiment was still conducted but only as a pilot study with author as the only subject. The results of this pilot study, supported by the findings of De Valois et al. (1986) and the complications mentioned, provide evidence against the surround flicker induced adaptation modulation strength. They show that comparison between flicker adaptation and surround flicker induced adaptation is difficult. Thus the modulation intensity of surround flicker induced adaptation cannot easily be verified. Further, the modulation intensity of surround flicker induced adaptation is most likely weaker than the intensity of flicker adaptation.

There might be a retinotopic map, as suggested by the theory of *neural filling-in*. The adaptation effect of surround flicker induced adaptation may just not be strong enough to cause an adaptation in the filled in cells.

This conclusion however, requires further research. Firstly, this means conducting the proposed study on the out of phase perception and repeating the pilot study as a proper study involving a substantial and representative number of subjects. Further this work proposed two additional experiments as altered variants of the experiments by Robinson and de Sa (2012, 2013). A conclusion on brightness representation in the human visual system is only possible after further researching the surround flicker induced adaptation.

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