THE SPATIAL EXTENT OF SIZE ADAPTATION EFFECT IN PERIPHERAL VISION

A Master's Thesis

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July 2019

I certify that I have read this thesis and have found that it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Arts.

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ABSTRACT

THE SPATIAL EXTENT OF SIZE ADAPTATION EFFECT IN PERIPHERAL VISION

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July 2019

It has been shown that prolonged exposure to a certain object size (i.e. size adaptation) alters the subsequent size perception such that the size of the latter appears more dissimilar to the adapted size (Pooresmaeili, Arrighi, Biagi, & Morrone, 2013). However, how much of the visual space is influenced by the size adaptation at a certain location remains unanswered. Here, in order to investigate the spatial extent of the adaptation effect, we tested the size adaptation effect at the adapted location and various non-adapted locations. In the first psychophysical experiment, we showed a mid-sized adapter stimulus and tested its influence on subsequent size perception at 5 locations. Results showed that the size perception at non-adapted locations was influenced by the adapter, although not as much as the effect at the adapted location. In the second experiment, we tested the size aftereffect at 15 different locations and mapped out the perceived size distortions over the visual field. Lastly, in the third experiment, we tested the effect of size adaptation with ring-shaped stimuli and found a substantially large effect just as in the second experiment. These findings overall suggest that the size adaptation does not only have a local effect but also the size perception in consequence of adaptation is being distorted throughout the visual field.

Keywords: Perceived Size, Psychophysics, Size Aftereffect, Temporal Context, Visual Adaptation.

ÖZET

ÇEVRESEL GÖRMEDE BOYUT ADAPTASYONU ETKİSİNİN MEKANSAL KAPSAMI

Altan, Ecem
Yüksek Lisans, Psikoloji
Tez Danışmanı: Doç. Dr. Hüseyin Boyacı
Temmuz 2019

Belirli bir nesne boyutuna uzun süre maruz kalmanın (başka bir deyişle boyut adaptasyonunun), sonraki boyut algısını adaptör boyutundan daha farklı görünecek şekilde değiştirdiği gösterilmiştir (Pooresmaeili, Arrighi, Biagi, & Morrone, 2013). Ancak, görsel alanın ne kadarının belirli bir konumdaki boyut adaptasyonundan etkilendiği yanıtsız kalmıştır. Burada, adaptasyon etkisinin mekansal kapsamını araştırmak için, adapte edilmiş ve edilmemiş çeşitli konumlarda boyut algısını test ettik. İlk psikofizik deneyinde, orta büyüklükte bir adaptör uyaranı gösterdik ve adaptörün sonraki boyut algısı üzerindeki etkisini 5 konumda test ettik. Sonuçlar, adapte edilmemiş konumlardaki boyut algısının, adapte edilmiş konumdaki etki kadar büyük olmasa da adaptör tarafından etkilendiğini göstermiştir. İkinci deneyde, boyut art-etkisini 15 farklı yerde test ettik ve görsel alandaki algılanan boyut bozulmalarını haritalandırdık. Son olarak, üçüncü deneyde, boyut adaptasyonunun etkisini halka şeklindeki uyaranlarla test ettik ve tıpkı ikinci deneyde olduğu gibi oldukça büyük bir etki bulduk. Bu bulgular genel olarak boyut adaptasyonunun sadece lokal bir etkiye sahip olmadığını ve adaptasyon sonrası boyut algısının bütün görsel alanda bozulduğunu işaret etmektedir.

Anahtar sözcükler: Algılanan Boyut, Boyut Art-etkisi, Görsel Adaptasyon, Psikofizik, Zamansal Bağlam.

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CHAPTER 1

INTRODUCTION

Perception of size is one of the most vital characteristics critical for survival of humans, since we are continuously in an interaction with our environment. Even for the most basic daily functions like holding an object or climbing up stairs, the size information plays a huge role. Yet, in some cases, our perception of size might not truly reflect the real size of an object, because perceived size depends on several cues present in the visual scene such as distance, relative size and the recent past of the visual input. Any discrepancy between these factors might result in a misinterpretation of size, as in the case of many well-known size illusions.

Size illusions are very useful tools to study perceptual processes as they reveal the mechanism of size perception in the brain (Murray, Boyaci, & Kersten, 2006; Fang, Boyaci, Kersten, & Murray, 2008). Understanding how an illusion works provides great information regarding the way our brain is processing the visual input. However, some size illusions have yet to be explained thoroughly. Moreover, especially the effect of temporal context on size perception remains mostly understudied.

This work presents our study on the temporal contextual influence on the perceived size and the spatial extent of this illusory effect. The main question of this work is how adapting to a certain size changes the subsequent size perception, and to what extent this influence is present in the visual space.

Within this framework, the present chapter introduces the main topic, gives some background information, evaluates the previous studies in the literature and explains the scope and significance of the current study. The main focus of our study is the effect of temporal context on size perception, however, other factors are also crucial for the perception of size. Therefore, in order to provide a complete picture of the size perception and the factors influencing it, the current chapter first gives a general background about size perception and then focuses on the temporal aspect of it. In the following three chapters, three psychophysics experiments are explained and the last chapter is allocated for general discussion and conclusions.

1.1. Visual perception and the role of context

We are surrounded by an extremely large amount of visual information in every bit of a moment. The whole information in the physical space is being projected onto the retina, and a complex process leading to a proper interpretation of the visual input starts. The ultimate perception comes into existence by means of a particular combination of the retinal image, the top-down processing and the contextual elements.

In order for a piece of visual input to be associated with a meaning, it usually has to be processed together with its context, as a whole [1]. The role of context in the visual perception has extensively been studied for centuries (See Albright & Stoner, 2002 for a review on the history). For example, processing of various visual properties such as color (Allred & Olkkonen, 2013), lightness (Gilchrist, 1977), orientation (Gibson & Radner, 1937) and motion (Duncan, Albright, & Stoner, 2000) have been found to be influenced by the context.

[1] What is meant by the context here and in the rest of the text is not only the spatial aspect such as the neighbor regions and the image background, but also the temporal aspect, meaning the recent past of the image.

1.2. Size Perception and Illusions

Size is not an exception to those attributes being determined and influenced by the context. In the classic study of Holway and Boring, the perception of size was shown to be closely linked to the perceived depth (1941). In their experiments, when the depth cues were available in the visual scene, observers could accurately match the size of two circles presented separately at different distances. However, when all depth cues were eliminated such that the estimation could be determined only by the retinal size of the circles, the accuracy of matched sizes drastically decreased.

The retinal size is also as important as the perceived depth but influences the perceived size in tandem with the distance information since the retinal size and the distance are interdependent to each other. Retinal size decreases as the object distance increases and vice versa. Despite that the retinal input and our distance to objects change continuously in daily life, we still perceive the objects as having the same size. This is the basis of an important principle of the size perception, that is, size constancy (Anstis, Shopland, & Gregory, 1961; Goldstein, 2013). Basically, an object's image on the retina gets smaller when it moves away, but at the same time, its perceived distance increases. These two compensate each other and the perceived size remains constant.

Emmert's law illustrates a good example for the size constancy. According to the law, after viewing a circle for a prolonged period of time (i.e. adaptation), the circle's afterimage appears large when the gaze is directed to a distant surface, and conversely it appears small when the projection surface (which the afterimage is reflected in) is near (Emmert, 1881; Boring, 1940). Despite the adapted area of the retina remains the same, the size of the afterimage changes. This is because the perceived size is being scaled in proportion to the distance (Kilpatrick & Ittelson, 1953).

In a more recent study on the afterimage size, Sperandio, Chouinard, and Goodale

(2012) have demonstrated that the cortical activity in the primary visual cortex (V1) represents the perceived size instead of the retinal size of an afterimage. Their results suggested that when the retinal image size was constant, the activity in V1 is modulated in line with the scaled perceived size, with respect to the distance cues.

Similarly, there are other fMRI studies showing that two discs of physically same (but perceptually different) size elicit different amounts of activated area in V1 (Murray et al., 2006; Fang et al., 2008; Schwarzkopf, Song, & Rees, 2011) when presented with a corridor background. A perceptually large and more distant object occupies larger V1 area and vice versa. This suggests that the depth information, presumably coming from the higher visual areas (Fang et al., 2008), modulates the perceived size and consequently the extent of the activated region in V1.

Although the size has been overly associated with perceived distance and visual angle, there is a considerable amount of other cues taking part in the size perception; one being the relative size. Nearby objects serve as a reference point for an accurate estimation of the target object's size (See Rock and Ebenholtz (1959) for a comprehensive study on the relational determination of size). This explains why sometimes we fail to understand the real size of an object with a uniform background which provides no relative size cue, especially in the photographs.

Studies have shown that the perceived size also depends on the retinal position of the object (Schneider, Ehrlich, Stein, Flaum, & Mangel, 1978; Baldwin, Burleigh, Pepperell, & Ruta, 2016). Schneider et al. (1978) have studied the perceived size of lines at various locations and found that lines appear smaller in the periphery as compared to those in the central location. Moreover, the effect of luminance on this eccentricity-related perceptual change has been reported (Bedell & Johnson, 1984). The latter study illustrated that the peripheral object appears smaller when the luminance is low, and vice versa.

In addition, visual perception of object size has been also found to be altered by sound (Takeshima & Gyoba, 2013), contents of working memory (Pan, Zuo, & Yi, 2013) and spatial transient attention (Anton-Erxleben, Henrich, & Treue, 2007; Gobell & Carrasco, 2005).

Since the perception of the object size is mostly dependent on contextual influences and various other factors, any inaccurate estimation of one may lead to an illusory size perception. An illusion can be simply defined as the perceptual deviation from reality. Despite the underlying mechanism of the most size illusions have yet to be known conclusively, it has been argued that the perceptual deviation from the physical size occurs often as a consequence of the inconsistencies among the size-related cues, and of failure to integrate those perceptual cues (Day, 1994, 1972).

In two of the most well-known examples of size illusions, the Muller-Lyer illusion and the corridor illusion (or the Ponzo illusion), perceived sizes of two stimuli having the same size appear to be different. In the corridor illusion (Figure 1.1 B), there are two same-sized objects positioned at perceptually different distances on a corridor background. The object placed at the perceptually further location looks larger than the one at the perceptually nearer location. The perspective in the background elicits a perceptual depth and an erroneous size judgment (but see Reardon & Parks, 1983). In the Müller-Lyer illusion (Figure 1.1 A), a line with inward fins at both endpoints looks smaller than the same-sized line with outward fins. These two lines respectively resemble the inner and outer corners of a room. Based on this, the illusion has been associated with depth perception (Zanforlin, 1967), but thereafter, this hypothesis has been challenged by various variants of the Müller-Lyer illusion, which induces similar perceptual effect and includes no depth cues (Day, 1972).

Unlike these two illusions, the Ebbinghaus illusion (Figure 1.1 C) does not include any depth information. In the Ebbinghaus illusion, a disc surrounded by larger

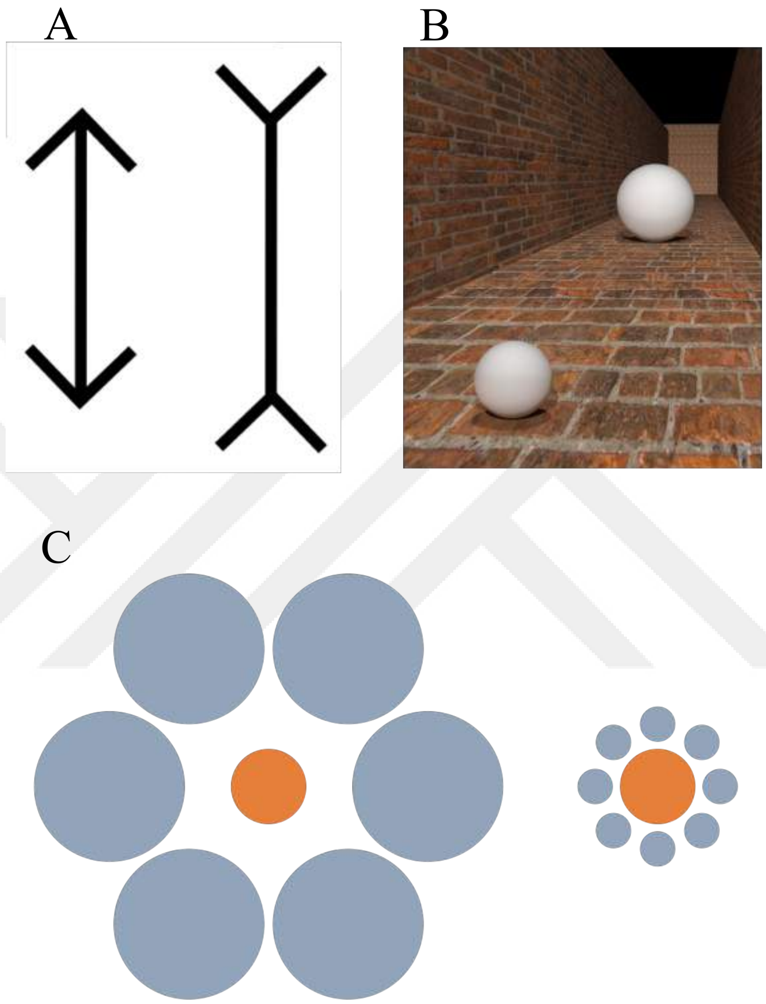

Figure 1.1: Examples of well-known size illusions. The two lines in the Müller-Lyer illusion (A), the spheres in the corridor illusion (B), and the orange discs in the Ebbinghaus illusion (C), have the same physical sizes, but due to the contextual influences, two stimuli appear to have different sizes.

discs (large inducers) is perceived as smaller than another disc of the same size which is surrounded by smaller discs (small inducers). This illusion is suggested to be due to the relative comparison judgment (Massaro & Anderson, 1971).

In addition to these spatial influences, there are also temporal contextual effects on perceived size. Blakemore and Sutton (1969) have shown that illusory size perception occurs after a prolonged viewing to another size.

1.3. Visual Adaptation to Size

Visual adaptation refers to the process of selectively adjusting the visual sensitivity of a stimulus feature, as a result of prolonged exposure to that particular feature (Webster, 2015; Clifford et al., 2007). Adaptation alters the neural response properties in order to maximize the coding efficiency of the visual system (Burr & Cicchini, 2014; Wainwright, 1999). However, gaining this efficiency has a trade-off: perceptual alteration in the adapted feature of the stimulus, known as aftereffect or adaptation effect. [2] Previous research has shown that multiple levels of visual processing adapts to various stimulus features such as color (Webster & Leonard, 2008), orientation (i.e. tilt) (Jin, Dragoi, Sur, & Seung, 2005), motion (Mather, Pavan, Campana, & Casco, 2008), shape (Suzuki & Cavanagh, 1998), glossiness (Motoyoshi, Nishida, Sharan, & Adelson, 2007), even faces and facial expressions (Watson & Clifford, 2003; Yang, Hong, & Blake, 2010).

In addition to all these, size is another stimulus submodality which is subject to the adaptation phenomenon. First and foremost, Blakemore and Sutton demonstrated the size aftereffect for the first time in 1969. They found that after prolonged exposure to a high-contrast grating pattern of a certain spatial frequency, subsequent perception of size shifts away from the adapted spatial frequency. The perceptual effect can be experienced easily with an example adapter and test stimuli in Figure 1.2. Note that the spatial frequency of the right pair of gratings (test gratings) are physically the same, but perceptually altered after the adaptation.

[2] These two terms are used interchangeably in the rest of the text.

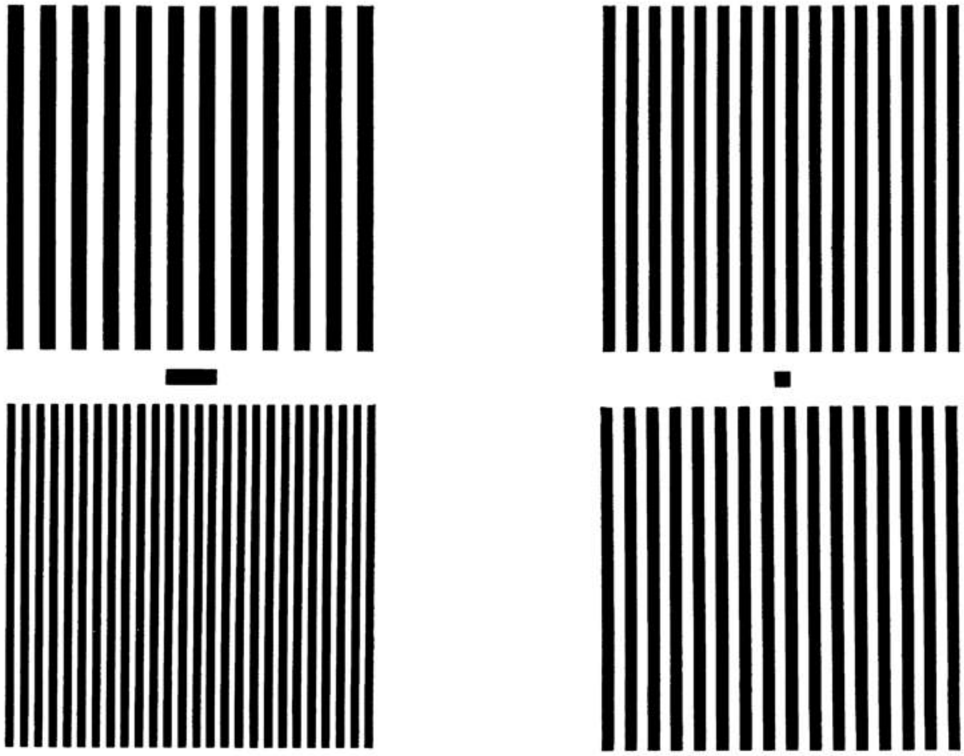

Figure 1.2: Illustration of the perceptual shift in the spatial frequency as a result of adaptation. When looked at the rectangle in the middle of the left gratings for around 1 minute, and then quickly shifted the focus to the square on the right, the spatial frequency of the right gratings appear to be altered so that the perceived frequencies are more dissimilar to those adapted. Reproduced from “Size Adaptation: A New Aftereffect”, by Blakemore and Sutton, 1969, *Science, 166*, p. 245. Copyright 1969 by The American Association for the Advancement of Science. Reprinted with permission.

In their experiments, Blakemore and Sutton have asked participants to adjust the spatial frequency of a grating at the bottom to match it with the one on top, while fixating in between the two. They tested a variety of different spatial frequencies (from 1.05 to 28.3 cycles per degree), after having them adapted to a certain spatial frequency (10 cycles per degree) and also without adaptation. Their results demonstrated that after 1 minute of adaptation period, a denser (higher spatial frequency) grating stimulus appeared even denser; and that a sparser (lower spatial frequency) grating appeared even sparser than the actual, as shown in the upper graph in Figure 1.3. These bidirectional perceptual shifts did not occur in the without-adaptation condition (open diamonds in the same graph).

They also tested the adaptation effect with various adapting frequencies and found a similar pattern of the aftereffect for each of the adapter gratings (see the middle graph in Figure 1.3). The graph at the bottom illustrates the normalized data from the various adapter frequencies.

Suzuki and Cavanagh (1998) have also found very similar results regarding the perception of various shapes as a result of adaptation. They used line, triangle and a curved shape, as the adapter and tested their effects respectively on a circle, a square, and a diamond without curvature. Results consistently showed that the test stimuli appeared more dissimilar to the adapter stimulus. For instance, when adapted to a vertical line, participants perceived a subsequently presented circle as being horizontally elongated. They explained the results with a shape-tuning model as shown in Figure 1.4. According to the model, each shape-sensitive neuronal unit (hypothetical shape channels, numbered from 1 to 7 in the figure) has a tuning curve for a particular shape. This means that normally each unit is maximally sensitive to a particular shape, and relatively less sensitive to the small variants of that particular shape. For example, when a perfect circle was presented, unit 4 would give the maximum response among others, but unit 2 would also give response although it would be much weaker. Unit 1, however, would not respond to a perfect circle at all, since its sensitivity curve does not

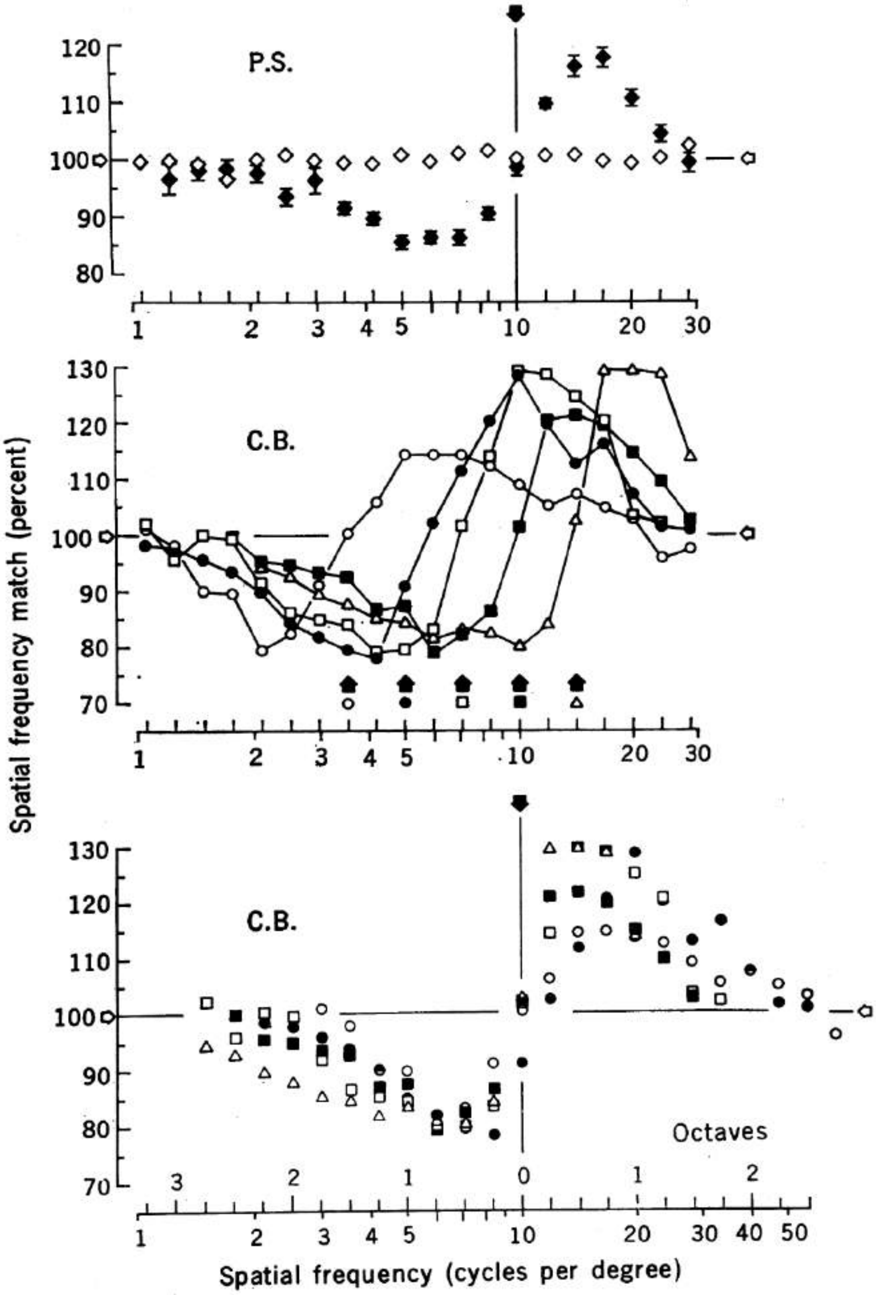

Figure 1.3: Results of Blakemore and Sutton (1969). x-axes show the spatial frequency of the gratings. y-axes represent the percent magnitude of the aftereffect. Values higher than 100 represent perceptual overestimation and values lower than 100 represent perceptual underestimation of spatial frequency. Reproduced from "Size Adaptation: A New Aftereffect", by Blakemore and Sutton, 1969, *Science, 166*, p. 246. Copyright 1969 by The American Association for the Advancement of Science. Reprinted with permission.

coincide with anywhere within the shape space of the circle. Activities of each unit form an overall response profile of the presented shape. The maximum value in this response profile (i.e. centroid) determines the perceived size.

Under normal circumstances (i.e. without adaptation), the profile of the distribution of unit responses to a perfect circle (also a square and a shape without curvature) has been presented in the upper graph (A) in Figure 1.4. A perfect circle would be perceived as it is, because the centroid corresponds to the circle in the shape space. Part B of Figure 1.4 depicts the altered sensitivity curves and a consequently shifted response profile, after adaptation to a vertical line (also to a triangle and a curved shape). The model suggests that the adaptation decreases the sensitivity of the units, proportional to their sensitivity to the adapter stimulus. After this diminution in the sensitivity curves, the response profile would also be changed such that the maximum value being shifted to a more distant place in the shape space.

This channel hypothesis has been widely accepted in the adaptation studies (Blakemore & Sutton, 1969; Blakemore, Nachmias, & Sutton, 1970; Suzuki & Cavanagh, 1998; Braddick, Campbell, & Atkinson, 1978; Mollon, 1974). But where are the size tuned units in the brain, if there are any?

Pooresmaeili et al. (2013) have investigated the role of the primary visual cortex (V1) in the size adaptation effect, using high-pass filtered (low spatial frequencies were eliminated from the image) Craik–O'Brien–Cornsweet circles. They conducted a behavioral experiment in which they aimed to test the perceptual effect of the size adaptation, and an fMRI study to reveal the cortical activation in response to the stimulus presented after the adapter stimulus. In the behavioral experiment, they presented the adapter stimulus on the 9 degrees left to the fixation point. After the adaptation phase, they presented a test stimulus at the same location as the adapter. And shortly after, a reference disc appeared on the right visual field. Participants were required to select the bigger disc at the end

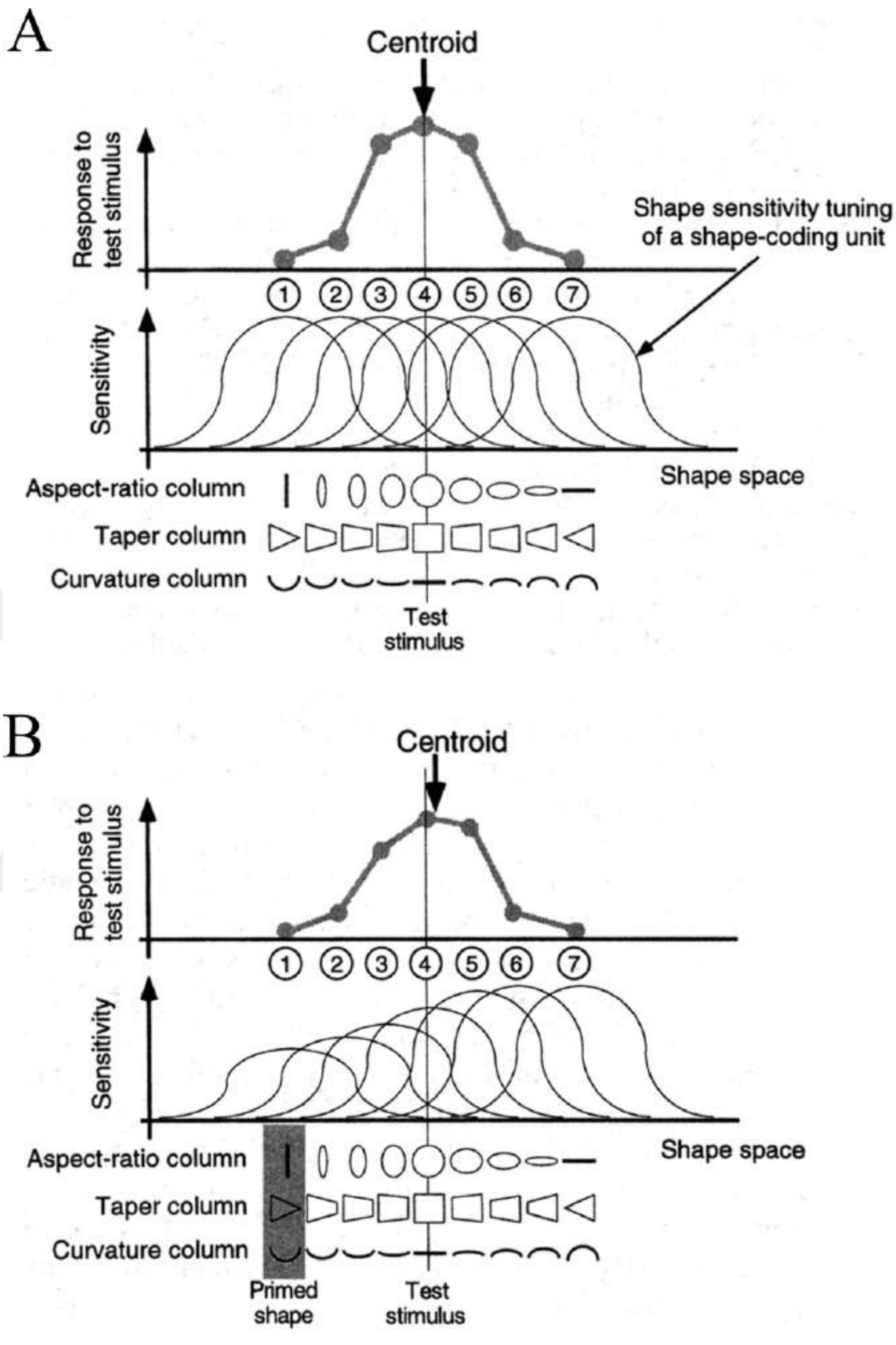

Figure 1.4: A model explaining the perceptual effect of adaptation to shape. Upper illustration (A) is for the shape perception under normal conditions (i.e. without adaptation). Below illustration (B) is for the distorted perception following an adaptation period. See text for the explanations. Adapted from "A shape-contrast effect for briefly presented stimuli", by Suzuki and Cavanagh, 1998, *Journal of Experimental Psychology: Human Perception and Performance, 24*, p. 1339. Copyright 1998 by the American Psychological Association, Inc.

of every trial. There were three sizes of the adapter: larger than, smaller than and equal to the test stimulus. Results were in line with the previous size adaptation studies. Large adapter caused the test to be perceived smaller, small adapter caused it to appear larger, and mid-sized adapter did not significantly influence the perceived test. In the fMRI experiment, Pooresmaeili et al. (2013) presented the same adapter and the same test stimuli while participants were passively viewing them in the scanner. As in the previous fMRI studies on illusory size perception (Murray et al., 2006; Fang et al., 2008; Sperandio et al., 2012), they found that the activation in V1 represents the perceived size, rather than the retinal size of the test stimulus. They also stated that the activated area in V1 correlated with the perceived size and concluded from these results that the local interactions in V1 are likely to be the origin of the size adaptation effect, suggesting feed-forward processing (See also Chouinard & Ivanowich, 2014, for a critical review).

On the other hand, there are studies supporting the feedback modulation on size adaptation effect. Kreutzer, Fink, and Weidner (2015) investigated the modulatory influence of the higher level visual areas where the attention can influence the size adaptation. They used an adaptation display in which the small and the large adapter was presented together, in order to keep the bottom-up stimulation constant for all conditions. There were three conditions in their experiment: inner-focus, outer-focus, and control. In the inner-focus condition, participants focused on the symbols forming the small adapter stimulus; in the outer-focus condition, they focused on the large adapter stimulus. Researchers found that the directed attentional focus determined the effect of adapter display on the subsequent perceived size. The perceived size of the test stimulus was decreased in the inner-focus condition as compared to the outer-focus condition and also as compared to the control condition. These results illustrated the effect of high-level modulation in size adaptation. In line with this study, Laycock, Sherman, Sperandio, and Chouinard (2017) reported that the adapter does not affect subsequent size perception when the participants are not consciously aware of the adapter stimulus.

The source of the adaptation effect seems not agreed on, but these studies aroused another important question: Is there a common size-scaling mechanism for both adaptation and spatial illusions? This question was addressed by Kreutzer, Ralph, and Fink (2015), via testing whether the perceptual effect adds up when the two contextual cues are presented together. They measured the perceived size and the corresponding cortical activity, under the manipulation of (1) Ebbinghaus inducers, (2) adapter stimuli, and (3) the combination of both. They found that the magnitude of the perceptual effect for the combined illusion did not increase further, but the fMRI results showed that the cortical activation for the combined illusion was higher than those found for both illusions separately. These results provide evidence for a shared mechanism which is limited in capacity.

1.4. The Present Study

Despite the wealth of research on the perception of size in a spatial context, and the wealth of research on visual adaptation, the effect of adaptation on size perception is under-studied. Recent studies on size adaptation (e.g. Pooresmaeili et al., 2013; Kreutzer, Fink, & Weidner, 2015; Laycock et al., 2017) have mainly addressed the source of the aftereffect but overlooked the spatial aspect of size (except Kreutzer, Ralph, & Fink, 2015). There is much to be understood about the temporal contextual influences on size perception and its relation with the visual space.

Likewise, previous studies on size adaptation have always tested the adaptation effect at the same visuospatial location as the adapter stimulus. Therefore, how much of the visual space is being influenced by the size adaptation remains unanswered. The current study addresses this gap in the literature and aims to reveal the spatial extent of the size aftereffect. The main questions of the current study are as follows: Does the prolonged exposure to a certain size alter the subsequent size perception at non-stimulated, non-adapted locations, too? If so, is the perceived size distortion the same over the whole visual space? And lastly, is there a pattern of perceived size distortions with respect to the test location's distance from the adapter?

In order to address these questions, three behavioral experiments were conducted. The common aspect in these three experiments was that the effect of adaptation to a certain-sized circular stimulus was tested at multiple locations including the classic overlapping location (adapter's location) and other locations which do not have a recent stimulation history. Further details of the experiments were provided at the beginning of each chapter. Results of experiments are expected to provide a valuable contribution to the literature regarding the size adaptation phenomenon. Results may have implications on size perception, and receptive field characteristics. Moreover, outcomes of this study will potentially motivate many other questions in size adaptation research, as well as in adaptation studies in general.

CHAPTER 2

EXPERIMENT I: NON-LOCAL EFFECT OF SIZE ADAPTATION WITH FILLED CIRCLES

In this chapter, the first experiment of the study is explained in detail. Besides, the present chapter serves as a base for the other experiments explained in the following two chapters, as it includes shared elements with those chapters, mostly regarding the design and the methodology.

The main purpose of the first experiment was to investigate the effect of size adaptation on subsequent size perception, at various locations, so that the spatial extent of the effect could be understood. Most parameters used in the experiment were either tested in the pilot studies or adapted from previous size adaptation studies in the literature.

2.1. Method

2.1.1. Participants

12 subjects (5 males, 7 females; age range: 22-33; $M = 26.2$; $SD = 3.59$) with normal or corrected-to normal vision participated in the experiment. Protocols and procedures were approved by the Bilkent University Human Ethics Committee. All participants gave written informed consent prior to experiment.

2.1.2. Stimuli and Apparatus

Stimuli were generated and presented via MATLAB (Mathworks), Psychophysics toolbox (Brainard, 1997). Participants seated 65 cm in front of a 30-inch NEC MultiSync LCD monitor (LCD3090WQXi; 60 Hz refresh rate; 1920×1200 screen resolution) in a dark room. A chin-rest was used to stabilize participants' head.

An instruction display was shown before the experiment. Participants read the instructions and continued with the experiment by a key press. Participants were asked to focus on the fixation point at the center of the screen throughout experimental blocks. In a single trial, there were two phases: Adaptation phase and test phase (See Figure 2.1). Two phases were separated by a short interval (300 ms). All durations were adopted from Pooresmaeili et al. (2013).

Adaptation: Adaptation phase included an adapter disc which was presented either always on the left or always on the right visual field (Figure 2.1 A shows an example of adapter disc presented on the right visual field) throughout an experimental block. This phase was present only in adaptation condition. Center-to-center distance between the fixation point and the adapter disc was set to 8° of visual angle. Duration of the adaptation phase was 40 s for the first trial, as an initial adaptation, and 7 s for the rest of the trials, as top-up adaptation. Adapter disc flickered from dark gray to light gray at 10 Hz in order to prevent formation of any afterimages. Diameter of the adapter disc was always 2.5°.

Test: Test phase consisted of two test discs: A reference disc and a variable disc. Reference disc was presented always at the same visual field as the adapter, and had a fixed size of either 1.5° or 3.5° (i.e. smaller or larger than the adapter). There were five positions of the reference discs: Four eccentric positions which were evenly spaced around the adapter; and one concentric with the adapter. See Figure 2.2 for the spatial arrangement of all reference disc positions. Eccentric positions were 4° away from the adapter's position, from center-to-center. Variable disc, on the other hand, was presented always at the non-adapted visual field, and its position was always symmetrical to the reference disc with respect to vertical center of the screen. Variable disc's size was subject to one-up one-down interleaved staircases. Figure 2.1 B shows an example view of the test phase, while the test discs were placed at one of the eccentric positions (e.g. up).

2.1.3. Procedure

Participants were given a short practice session immediately before the first experimental block for once, to make sure that they follow the instructions. The experiment consisted of 4 blocks of adaptation condition. A single block included 250 trials in total, for the five test positions (nearer, further, up, down, and center; see Figure 2.2) and two separate staircases for each position. Participants were required to compare the sizes of reference and variable discs and to indicate the bigger test disc by pressing one of the two arrow keys (either left or right) on a keyboard in all trials. Using one-up one-down adaptive staircase method, the diameter of variable disc was updated after each trial, depending on the response of participants: If the response indicates that the variable disc was bigger than the reference, the variable got smaller in the following trial, and likewise, if the response indicates that the reference was bigger than the variable, then the variable disc got larger in the next trial of the same staircase. In the first couple of trials, variable discs of both staircases started from well-above and well-below the perceived size of reference disc, so that the participants could easily make the judgment. As the trials proceed normally, sizes of the variable disc and the reference disc became more and more indistinguishable because the size of the variable disc gets closer to the perceived size of reference disc.

In order to avoid participant strategies and trial to trial dependencies, all five positions and two staircases were presented in a random order. Each staircase consisted of 25 trials, providing 50 trials in total for the measurement of a single test location. The number of trials was determined carefully in the pilot studies. The increment/decrement factor for the size of the variable disc, called step size,

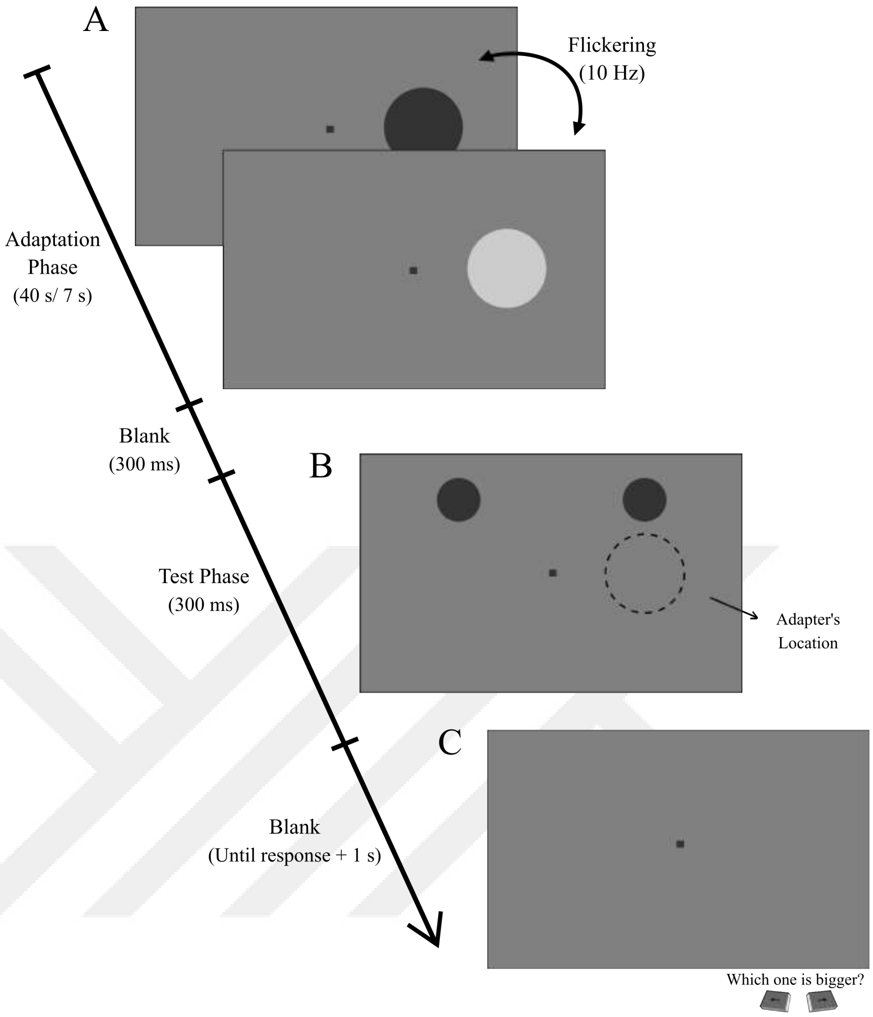

Figure 2.1: Time course of a single trial in Experiment I. Fixation point was always present at the center of the screen in the experiment. The time-line arrow represents the event sequence for adaptation condition. Every trial in the adaptation condition started with an adaptation phase (A). Adapter stimulus flickered from dark gray to light gray at 10 Hz and was presented either at the left or the right visual field (in this case right visual field). Adaptation phase lasted 40 s in the first trial, 7 s in the rest of the trials in a block. It was followed by a blank fixation screen (same as C), presented for 300 ms. (B) Test phase appeared with a reference disc in one of the five positions at the adapted visual field, and a variable disc at the non-adapted visual field. The position of the variable disc was always symmetrical to the reference disc with respect to the vertical center of the screen. Test phase lasted 300ms. (C) After the test phase, participants were required to press a key to indicate bigger test disc comparing sizes of the reference disc and the variable disc, while maintaining their fixation. The blank fixation screen remained until 1 second after they responded.

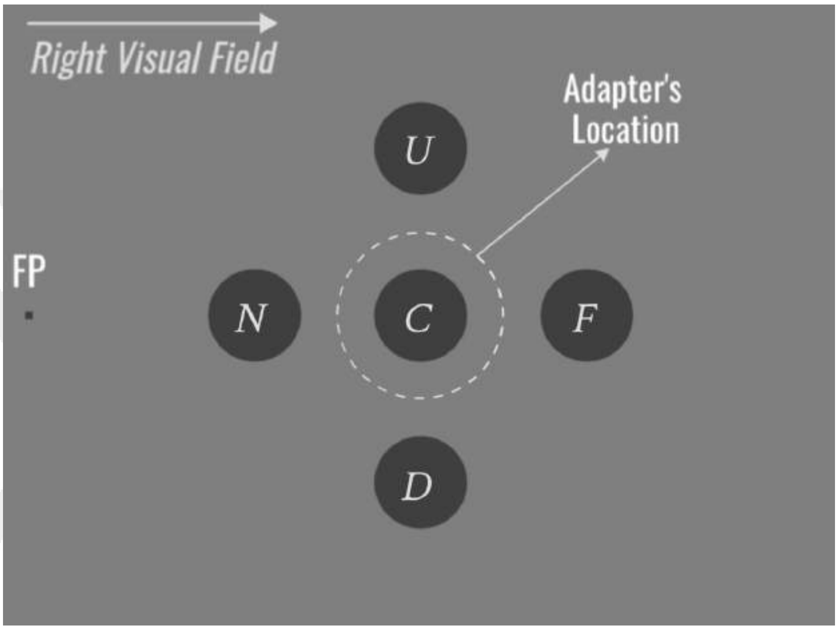

Figure 2.2: Spatial layout for all positions tested in Experiment I. Figure was generated for the combination of small disc size and right adaptation conditions. Only the right visual field is shown for simplicity. Filled dark gray discs show the positions of the reference discs presented in the test phase. The distance between the eccentric discs and the adapter was 4 degrees from center to center. White dashed circle represents the location of preceding adapter stimulus. Note that the reference discs were presented at one of these five positions at a time, in separate trials. FP: fixation point, N: nearer, U: up, C: center, D: down, F: further.

was set to 0.32° at the beginning but decreased by half after each reversal of response, until it reached to 0.04° of visual angle.

The aforementioned procedure describes a single block of the experiment. In 4 separate blocks, two test sizes (small and large - as compared to the adapter) were tested in both visual fields (left and right) in order to eliminate possible hemispheric asymmetries in perceived size. Four combinations of test sizes and visual fields were given in separate sessions with a random order. In addition, participants observed and responded to the control blocks of all combinations as well. Control blocks were the same as the adaptation blocks, except that the adaptation phase was absent. In other words, participants completed the experiment in 4 separate sessions, each including one control block and one adaptation block. Time interval between sessions ranged from 2 hours to days.

An adaptation block and a control block were randomly assigned to each session; however, within the sessions, the control block always preceded the adaptation block, in order to rule out the possible prolonged effect of adaptation on control trials. A short break was given in between the control and the adaptation blocks.

2.1.4. Data Analysis

Using Psignifit 4 MATLAB Toolbox (Schütt, Harmeling, Macke, & Wichmann, 2016), each subject's measurements for each condition were fitted with Logistic function with given parameter specifications. Parameters for lapse and guess rate were fixed to 0.01. The overdispersion parameter was kept free, allowing program to estimate overdispersion value of each measurement. The point of subjective equality (PSE) values were derived from the fitted function. In the present study, the point of subjective equality [PSE] value is a certain size of the variable disc which is perceptually identical to that of the reference disc for the participant. It corresponds to half proportion that the reference disc seen as bigger. For each subject, 40 PSE values were calculated in total ([5 test positions] × [2 sizes of reference disc] × [2 positions of adapter] × [2 control vs adapter]).

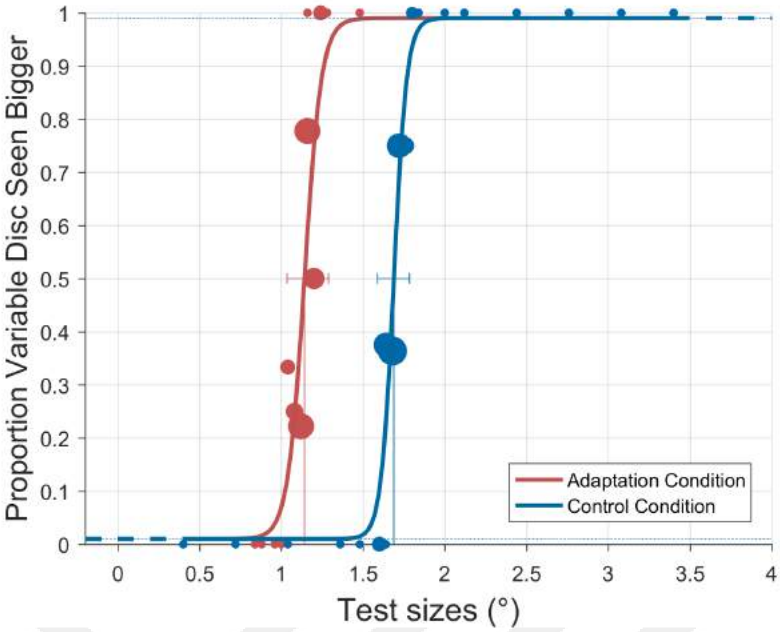

Figure 2.3: A sample data set (Subject GB). Red color represents the condition in which the adaptation was presented at the left visual field and followed by small (1.5°) reference disc located at the center position; blue color represents the control condition of the same specific combination at the same position. Error bars represent 95 % confidence interval for the PSE values given by Psignifit 4.

Sample data of an adaptation condition and the corresponding control condition gathered from Subject GB are shown in Figure 2.3. Positions of circles in the figure show the proportion of responses indicating the reference stimulus as bigger for each test size presented in the experiment. Size of these circles represents the total number of trials in which corresponding reference disc size has been tested. Circles get bigger as the number of measurement of the same reference disc size increases.

For further analyses, we calculated the percent change between the actual size and the perceived size for each measurement:

$$\text{Percent change in perceived size} = \frac{\text{PSE} - \text{Reference size}}{\text{Reference size}} \times 100. \tag{2.1}$$

Then, we calculated the adaptation effect index by subtracting the perceived sizes of the control condition, from those of the adaptation condition:

$$\text{Adaptation Index} = \frac{\text{PSE}_{Adaptation} - \text{PSE}_{Control}}{\text{Reference size}} \times 100. \tag{2.2}$$

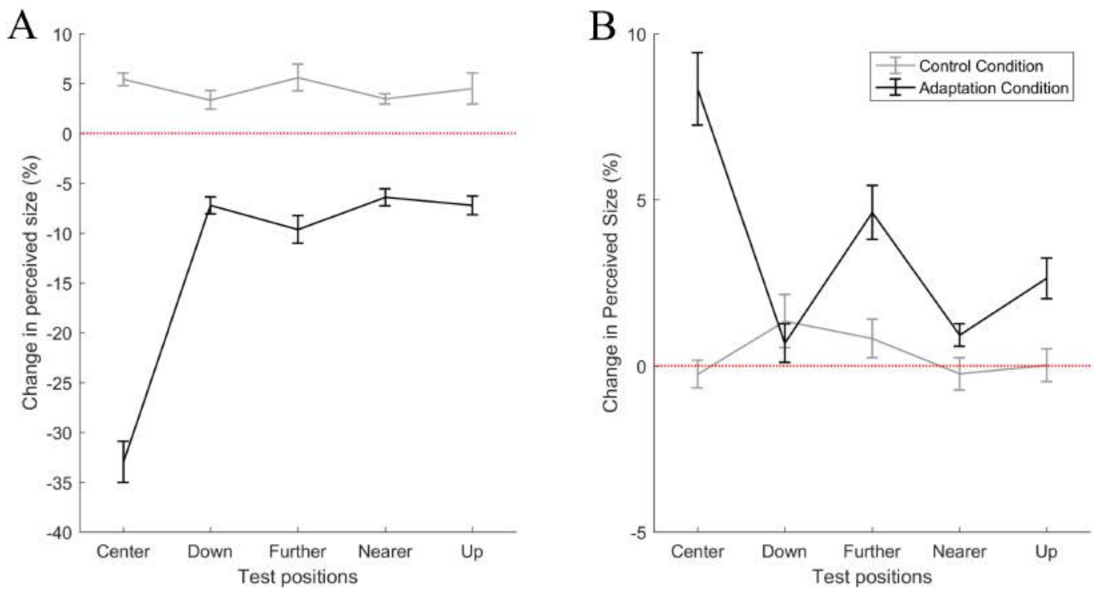

Figure 2.4: Results of Experiment I. Vertical axes represent percent change in perceived size for small (A) and large (B) reference discs. Positive and negative values of percent change represent the direction of the effect. Below zero means that the perceived size is smaller than the actual size, and above zero means the opposite. Horizontal axes show five different positions in which perceived size was tested. Error bars: standard error.

Obtained values of adaptation index give the magnitude of the mere perceptual effect caused by the adaptation.

JASP software was used for the statistical analyses (JASP Team, 2018). The same statistical analyses were performed for small test condition and large test condition, separately. First, percent perceived size changes for adaptation and control conditions were compared via repeated measures t-test. Single tailed t tests were used as we have a strong a priori knowledge about the direction of the size aftereffects. Then a repeated measures ANOVA was performed with adaptation index values to test the effect of reference disc positions and adapter region on the adaptation effect.

2.2. Results

2.2.1. Small Test Size

On average of two visual fields, small reference discs presented at center position were perceived 38.4($\pm$2.4 *SEM*)% smaller in the adaptation condition as compared to those in the control condition. Likewise, perceived sizes of reference discs were 10.6($\pm$1.1 *SEM*)%, 15.2($\pm$2.2 *SEM*)%, 9.9($\pm$0.8 *SEM*)%, 11.7($\pm$1.7 *SEM*)% smaller at positions down, further, nearer and up, respectively (See left panel of Figure 2.4). In order to see whether the difference between adaptation and control conditions were statistically significant, five paired samples t-tests were conducted. Single tailed paired samples t tests showed that the difference between the two conditions was statistically significant for all of the five reference disc positions (corrected ps $< .001$; see Appendix B.1 for details). Multiple comparisons were corrected via FDR procedure (Benjamini & Hochberg, 1995; Groppe, 2010).

We then conducted a two-way repeated measures ANOVA with the adaptation index values as dependent variable. As independent variables, we had two within-subject factors: Adapter region (left visual field, right visual field) and reference disc position (center, down, further, nearer, up). Repeated measures ANOVA revealed that there is no significant main effect of adapter region, meaning that the visual field in which the adapter has been presented did not differ significantly from each other in terms of adaptation index ($F(1, 11) = 1.006$, $p = 0.337$). As for the factor of reference disc position, the sphericity assumption of the repeated measures ANOVA has been violated (Mauchly's sphericity test revealed a significant result $\chi^2(9) = 24.43$, $p < .01$). Thus, in order to have a valid F value, degrees of freedom has been corrected with Greenhouse-Geisser correction. There was significant main effect of the reference disc position ($F(1.97, 21.63) = 50.35$, $p < .001$). The interaction between adaptation region and reference disc position was not significant ($F(4, 44) = 1.63$, $p = .184$).

Post hoc comparisons showed that the adaptation index at center position was significantly greater than the rest of the positions (Bonferroni corrected ps $< .001$). Eccentric positions were not significantly different from each other.

2.2.2. Large Test Size

Large reference discs presented at the center position were perceived 8.6($\pm$1 *SEM*)% larger in the adaptation condition compared to the control condition, on average of two visual fields. Likewise, reference discs presented in the three of the eccentric positions were also perceived larger in the adaptation condition (Up: 2.6% $\pm$0.9 *SEM*; Nearer: 1.2% $\pm$0.7 *SEM*; Further: 3.8% $\pm$0.9 *SEM*). One tailed paired samples t tests showed that the percent changes in perceived size was statistically significant for three of the five reference disc positions (FDR-corrected ps $< .01$; see Appendix B.1 for details.).

Repeated measures ANOVA was conducted with the same factors as the ANOVA for small reference disc. Adapter region revealed significant main effect ($F(1, 11) = 6.407$, $p < .05$). Main effect for reference disc position was also significant ($F(4, 44) = 16.26$, $p < .001$). The interaction between adaptation region and reference disc position was not significant ($F(4, 44) = 2.52$, $p = .054$).

Bonferroni corrected post hoc comparisons showed that there was significant difference between center position and the rest of four positions in the adaptation indices. In detail, adaptation index for center was significantly greater than that for down ($p < .001$); further ($p < .05$); nearer ($p < .01$); and up ($p < .05$). Since the significant differences between the eccentric positions were not related to the current hypotheses, they were not mentioned here (but can be found in Appendix B.1). Lastly, post hoc test for the adapter region revealed that the adaptation effect in the left visual field was significantly stronger than that in the right visual field ($p < .05$).

2.3. Discussion

In this experiment, we investigated the effect of adaptation on perceived size for two test sizes in five different positions. Results showed that being exposed to a certain disc size influences the subsequent size perception such that the latter size being more dissimilar to the adapted size. The pattern of adaptation effect for both small and large reference stimuli was similar, although the direction and the magnitude of the effect were different. In this regard, the adaptation effect at center positions of small and large test discs were consistent with those in literature. In addition, we observed strong perceptual effects in the eccentric positions in which the reference discs did not overlap with the adapter. This is the most remarkable finding as it indicates that the size adaptation has a non-local influence, which also implies a global distortion in the size perception.

CHAPTER 3

EXPERIMENT II: NON-LOCAL EFFECT OF SIZE ADAPTATION WITH FILLED CIRCLES IN A WIDER SPATIAL EXTENT

In the previous chapter, we provided evidence that the adaptation effect is observed not only at the exact position of the adapter, but also 4 degrees away from it. Present chapter introduces the second experiment of the study which expands the scope of the previous results.

In this experiment, we aimed to find out whether the adaptation effect is present at even further locations than those tested in the first experiment, and to form a depiction of perceived size distortions over the visual field caused by the size adaptation. To do so, we tested the adaptation effect at 15 different positions with a similar method and experimental procedure to those in the Experiment I.

3.1. Method

3.1.1. Participants

We have collected data from 3 different groups of subjects, with 12 subjects in each group. All subjects had normal or corrected-to-normal vision and gave informed consent before the experiment. Each group of subjects participated in different

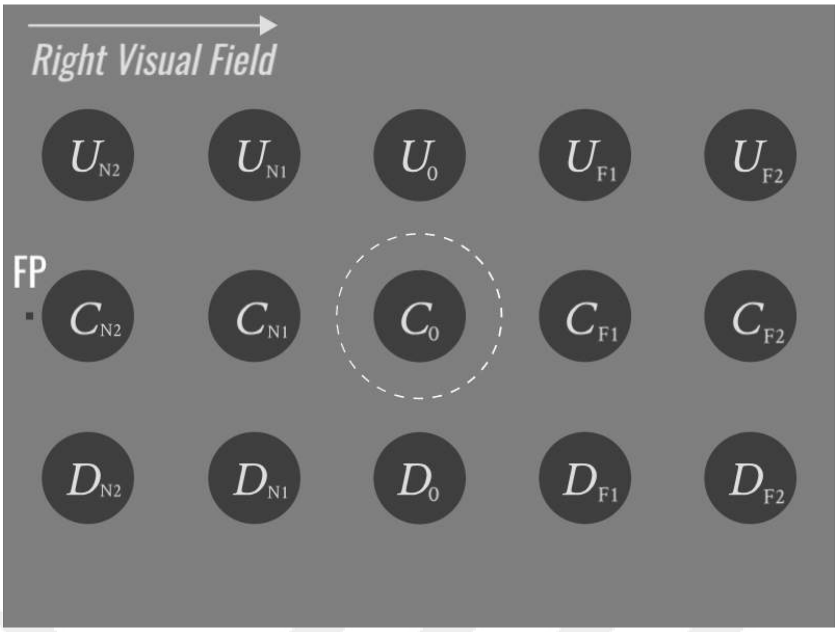

Figure 3.1: Spatial layout for all positions tested in Experiment II. Figure was generated for a combination of small reference disc size and right adaptation conditions. Dark gray discs represent reference discs and white dashed circle represents the size and position of the adapter disc. Only right visual field is shown here for simplicity. Note that 1 out of 15 possible test disc was presented at a time in the test phase, accompanied by its corresponding variable disc at the other visual field. FP: fixation point, U: up, C: center, D: down, N2: nearer 2, N1: nearer 1, 0: zero, F1: further 1, F2: further 2.

parts of the experiment at different times. First group (6 males, 6 females; age range: 22-32; M = 25.9; SD = 2.84) was tested for the center row in Figure 3.1, second group (5 males, 7 females; age range: 18-21; M = 19; SD = 1.13) was tested for the upper row, and third group (6 males, 6 females; age range: 18-26; M = 19.7; SD = 2.64) was tested for the lower row in the same figure. Protocols and procedures were approved by the Bilkent University Human Ethics Committee.

3.1.2. Stimuli and Apparatus

Stimuli were generated and presented via MATLAB, Psychtoolbox (Brainard, 1997). Experiment was conducted under the same physical conditions as in Experiment I. Instruction display was also the same, so participants were asked to fixate on the dot at the center of the screen throughout the blocks. Stimuli were mostly the same as those used in Experiment I with some exceptions as described below.

Adaptation: Flickering adapter was presented 10° away from the fixation point (instead of 8°), either at the right or the left visual field.

Test: Test phase included a reference disc and a variable disc at a time, as in the previous experiment. Differently from Experiment I, test phase covered three vertically aligned groups (rows) of test positions: up, down and center (abbreviated with their initial letters). Each vertical group included horizontally lined up five test positions (columns): nearer 2, nearer 1, zero, further 1, and further 2 (abbreviated as N2, N1, 0, F1, F2, respectively). Therefore, there were 15 different positions in total, for the test discs. Figure 3.1 shows their spatial arrangement. Reference discs at C_0 position (Vertically at center; horizontally at zero) was concentric with the adapter disc. Each test position was separated by 4° from their horizontal and vertical neighbour positions.

3.1.3. Procedure and Data Analysis

Procedure and the data analyses were the same as in Experiment I. Since we could not recruit the same group of participants for all test positions, we repeated the procedure for each row of test positions with different groups of subjects. Therefore, there was an additional between-subject factor in the statistical analyses.

Statistical analyses were performed separately for small and large test sizes. Paired samples t tests were performed to reveal whether perceived sizes differ among the adaptation and the control conditions and a mixed ANOVA was performed to show whether there is any effect of adaptation region, and reference disc positions (both within-subject and between-subject) on the adaptation effect index.

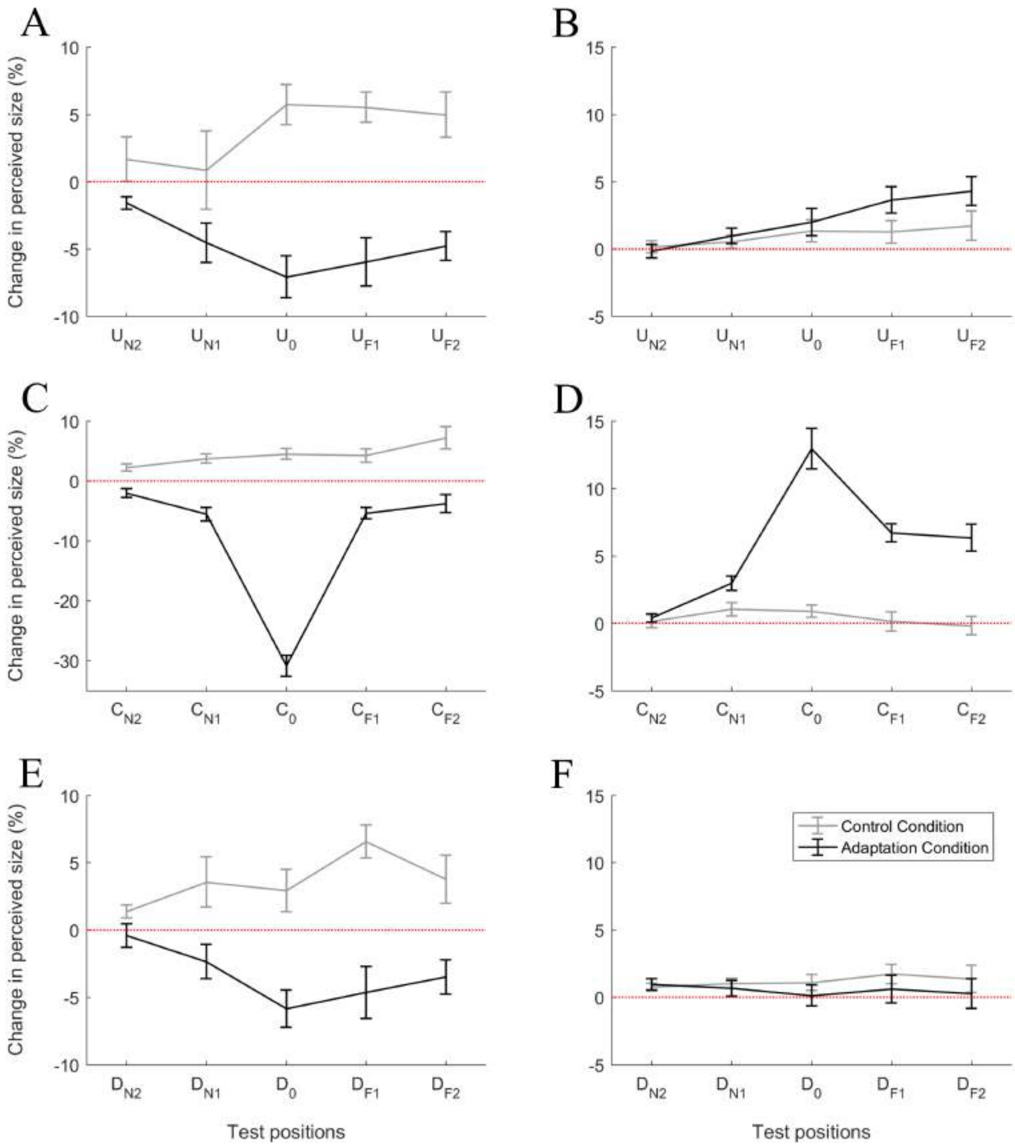

Figure 3.2: Results of Experiment II. Figure demonstrates the percent changes in perceived size (y-axes) of small and large reference disc sizes (respectively, left and right panels) at five locations (x-axes). Positive and negative values in y-axes represent the direction of the effect: values below/above zero represent perceptual underestimation/overestimation of reference stimulus size. First row (A and B) illustrates up positions, middle row (C and D) illustrates center positions, and third row (E and F) shows data for down positions. Error bars: standard error. U: up, C: center, D: down, N2: nearer 2, N1: nearer 1, 0: zero, F1: further 1, F2: further 2.

3.2. Results

3.2.1. Small Test Size

On average of two visual fields, small reference discs at C_0 position were perceived 35 ($\pm$1.5 *SEM*)% smaller in the adaptation condition as compared to those in the control condition. Perceived sizes in all of the 14 eccentric positions were also smaller than the actual sizes, with weaker percent changes, as shown in the left panels of Figure 3.2 (Panel A, C, and E).

Paired samples t-tests showed that the perceived sizes of small discs in the adaptation condition were significantly different than those in the control condition, at all of the 15 positions (FDR corrected ps < 0.05; see Appendix B.2 Table B.3 for details).

A mixed ANOVA with two within-subject factors and a between-subject factor was conducted. Within-subject factors are as follows: Adapter region (2 levels: left and right visual fields) and horizontal test positions (5 levels: nearer 2, nearer 1, zero, further 1, further 2). Between-subject factor was vertical test positions (3 levels: up, center, down). Dependent variable was adaptation index. Mauchly's test of sphericity showed that the sphericity assumption was violated for horizontal test positions and its interaction with the adapter region ($p < 0.001$ for the main effect of reference disc position and $p < 0.05$ for the interaction). Degrees of freedom were corrected via Greenhouse-Geisser sphericity corrections. Within subjects effect of ANOVA revealed that there was a significant main effect of the adapter region ($F(1, 33) = 9.27$, $p < 0.01$), and a significant main effect of the horizontal test position (Sphericity corrected; ($F(2.62, 86.52) = 36.32$, $p < 0.001$)). The interaction between the adapter region and the horizontal test positions was also significant (Sphericity corrected; ($F(2.87, 94.74) = 3.78$, $p < 0.05$). Between subjects effect of the analysis showed that there was a significant effect of vertical test positions ($F(2, 33) = 7.86$, $p < 0.01$). However, since the interaction between the horizontal test positions and vertical test positions was significant (Sphericity corrected; $F(5.24, 86.52) = 13.08$, $p < 0.001$), the effect of vertical test positions may be misleading alone. Therefore, simple main effect analysis was performed. The difference among the levels of vertical test positions was tested for each levels of horizontal test positions. The analysis revealed that the difference (among the levels of vertical test positions) was significant only at zero position of horizontal test positions ($p < 0.001$), meaning that the vertical test positions do not significantly differ from each other except at zero position.

Post hoc comparisons for the horizontal test positions revealed significant difference between zero position and all eccentric positions (Bonferroni corrected *p*s < 0.05). Other significant differences among eccentric positions (which can be found in Appendix B.2) were not mentioned here as they are irrelevant to the hypotheses. Pairwise comparison for the adapter region showed that the adapter presented in the left visual field had a stronger perceptual effect compared to that in the right visual field ($p < 0.01$)

3.2.2. Large Test Size

Large reference discs at C_0 position were perceived 12 (± 1.7 *SEM*)% larger in the adaptation condition as compared to the control condition, on average of left and right visual fields. 9 out of 14 reference discs presented at the eccentric positions were also perceived larger than the veridical in the adaptation condition. Paired samples *t*-tests revealed significant effect of adaptation in 4 of the 15 positions (FDR corrected *p*s < 0.05; see Appendix B.2 Table B.3 for details). Results for the large test size were shown in right panels of Figure 3.2 (Panel B, D, and F).

A mixed ANOVA was performed with the same within and between factors as those tested in the small test size analysis. Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the horizontal test position ($p < 0.001$) and the interaction between the horizontal test positions and the adapter region ($p < 0.001$). Greenhouse-Geisser correction was used to correct degrees of freedom. Within subjects effects of the ANOVA showed that there was significant main effect of adapter region ($F(1, 33) = 12.14$, $p < 0.01$) and of horizontal test positions (Sphericity corrected; $F(2.69, 88.79) = 13.16$, $p < 0.001$). Also, there was a significant interaction between adapter region and horizontal test positions (Sphericity corrected; $F(2.38, 78.40) = 3.67$, $p < 0.05$). Between subjects effect showed that there was a significant effect of vertical test positions ($F(2, 33) = 14.23$, $p < 0.001$). Since there was a significant interaction between the vertical test positions and horizontal test positions (Sphericity corrected; $F(5.38, 88.79) = 13.64$, $p < 0.001$), a simple main effect analysis was performed. The difference among the levels of vertical test positions was significant at zero ($p < 0.001$), further 1 ($p < 0.001$), and further 2 ($p < 0.01$) positions.

Post hoc comparisons for the horizontal test positions showed that the adaptation index at zero position was significantly different from that at nearer 1 and at nearer 2 (ps < 0.05), but not significantly different from that at further 1 and at further 2 positions. Post hoc analysis for the adapter region revealed that the left adapter condition produced significantly stronger effect than the right adapter condition ($p < 0.01$).

3.3. Adaptation Index Maps

In order to have a better understanding of the findings and the spatial extent of the adaptation effect, we visualized the adaptation effect spreading over the visual field. We first averaged two levels of adapter region (left adapter and right adapter) of 12 subjects, and then averaged all subjects for each of the 15 test positions. Although the left and the right visual fields revealed significantly different adaptation index values, as mentioned in the previous section, the change in the perceived sizes were in the same direction in both visual fields. To be more precise, underestimation of size was observed for small reference discs, and overestimation of size was observed in large reference discs; regardless of the visual field. After averaging, we ended up with a grid data consisting of 15 mean adaptation index values. Intermediate values were estimated by natural neighbor interpolation via

MATLAB (version R2016b). Interpolated points together with actual data points were plotted as shown in Figure 3.3 and Figure 3.4.

Figures show the spread of the adaptation effect, respectively for small and large test sizes. Axes of both figure show all positions tested in Experiment II. Colormap indicates both the magnitude and the direction of perceptual effect. The magnitude of adaptation effect was demonstrated with shades of both colors. Darker shades indicate stronger effects and vice versa. On the other hand, the direction of the effect was represented with the two colors. Red color shows the perceptual underestimation (negative index values) and blue represents the perceptual overestimation (positive index values) of the reference disc sizes. For example, middle areas (i.e. C_0 position), colored by the darkest shade of red in Figure 3.3, show the location at which the adapter causes the strongest perceptual underestimation (more than 30%, in this case) of reference stimulus size. Note that the same colormap was used to display different range of percent adaptation index in two figures.

Thick black circle at the C_0 position represents the adapter disc's size and location. Thinner green circles represent the positions and sizes of each reference disc presented in the experiment. These circles are smaller than the adapter in Figure 3.3; and larger than the adapter in Figure 3.4. Sizes of the circles (relative to the adapter) and distances between them were displayed proportionate to the actual stimuli presented to the participants. Yellow circles show the perceived sizes of reference discs at each location. At some locations, green and yellow circles overlap and there seems to be a single disc, because the perceived size was not much different from the actual size at those areas. Lastly, a small black square in the middle of the y-axis was added to indicate the location of the fixation point. Although the position of fixation point may imply that the results belong to the right adapter conditions, figures were generated for the average of left and right adapter conditions.

The significance stars in the figures belong to the results of t-test analyses which indicate the difference between the adaptation and the control conditions with FDR corrected p values.

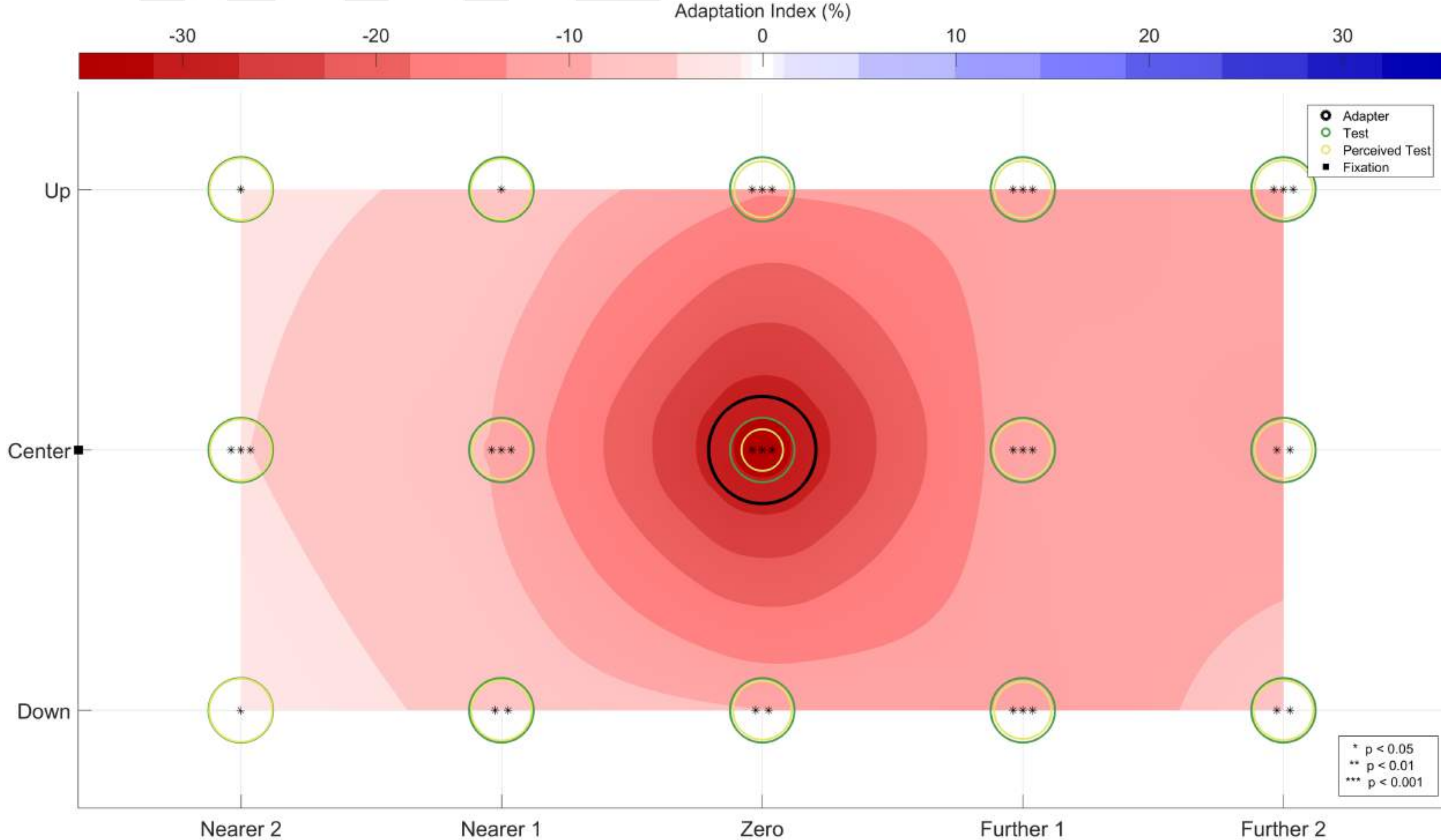

Figure 3.3: Adaptation index map and true-to-scale view of all stimuli for small reference disc size. See text for details.

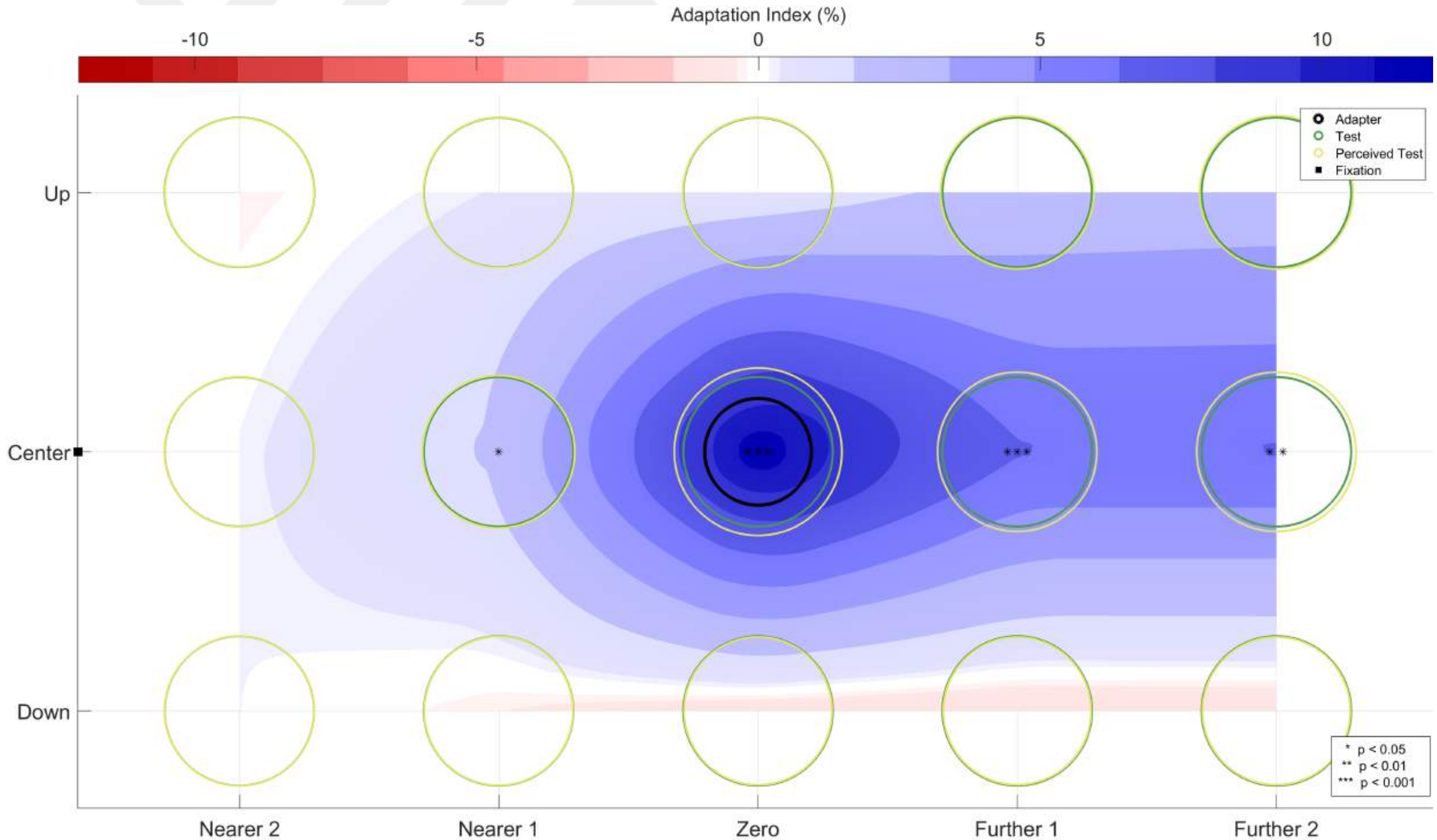

Figure 3.4: Adaptation index map and true-to-scale view of all stimuli for large reference disc size. See text for details.

3.4. Discussion

The scope of Experiment I has been extended in Experiment II, by testing the effect of size adaptation on a broader visual area. The size adaptation effect was tested on two test sizes at fifteen different locations. Results of this experiment replicated the findings of previous experiment and illustrated that the effect is more far-reaching than we already have found, especially for the small reference discs. Different from the previous experiment, we found significantly stronger effect on left visual field for small test size, too.

We also visualized the data and plotted adaptation index maps in order to depict the visual space of size perception, following an adaptation period. The adaptation index maps for small and large discs clearly show the strong distortion effect over a wide area of visual field. Unlike the map for the small discs, the map for the large discs showed a horizontally elongated pattern of the adaptation index. This might be related to the receptive field characteristics of neurons responding to the large discs, given that the shape of receptive fields can be elliptical (Hubel & Wiesel, 1959).

Findings of this experiment suggests that the size adaptation distorts the whole visual field, so that the size of subsequently viewed disc on that visual field is being perceived to some extent different from its physical size.

CHAPTER 4

EXPERIMENT III: NON-LOCAL EFFECT OF SIZE ADAPTATION WITH ANNULI

We investigated the size aftereffect and its spatial extent thoroughly in two experiments, as elucidated in the last two chapters. In those experiments, both the adapter and the test stimuli were filled circles (discs). One may argue that the local stimulation of neurons, whose receptive fields correspond to the inner parts of the adapter disc, somehow have an influence in the magnitude of illusion or in the illusion itself, and thus, the effect of adaptation is largely related to low-level features of the stimulus, irrespective of the size. In order to test this, in Experiment III we have repeated the size adaptation experiment using rings (i.e. annuli), instead of discs, since the size information would still be present without inner parts of the disc.

The main purpose of this experiment was to better understand the size adaptation phenomenon, using a different stimulus. Ring stimulus would give a clue to the neural mechanism of the size adaptation as it enables us to measure the perceived size without stimulating the whole neuron population falling within the retinotopic area of the adapter. In other words, with rings, we aimed to eliminate the size-irrelevant activation in the brain.

4.1. Method

4.1.1. Participants

12 subjects (4 males, 8 females; age range: 22-33; $M = 25.1$; $SD = 2.97$) participated in the study after giving their written consent. All participants had normal or corrected-to normal vision. Protocols and procedures were approved by the Bilkent University Human Ethics Committee.

4.1.2. Stimuli and Apparatus

Physical conditions of Experiment III were the same as those of previous experiments. We used the same experimental design with few exceptions. First, both adapter and test stimuli were annuli with a line-width of 0.18°. Second, we tested only 5 of the 15 positions which have been named as center positions in the second experiment (See Figure 4.1). The shape of annuli was obtained by adding a mid-gray disc (background color), on top of both adapter and test discs of Experiment II. Hence, sizes and distances used in this experiment were exactly the same as those in the previous experiments.

4.1.3. Procedure and Data Analysis

Procedure and the data analyses were the same as in Experiment I. Same statistical analyses were performed separately for small and large reference rings. First, single tailed paired samples t tests were performed to identify whether the perceived sizes of reference rings in the adaptation condition were significantly different from those in the control condition. Then repeated measures ANOVA was performed to reveal the effect of the adapter region, and the reference ring positions on adaptation index.

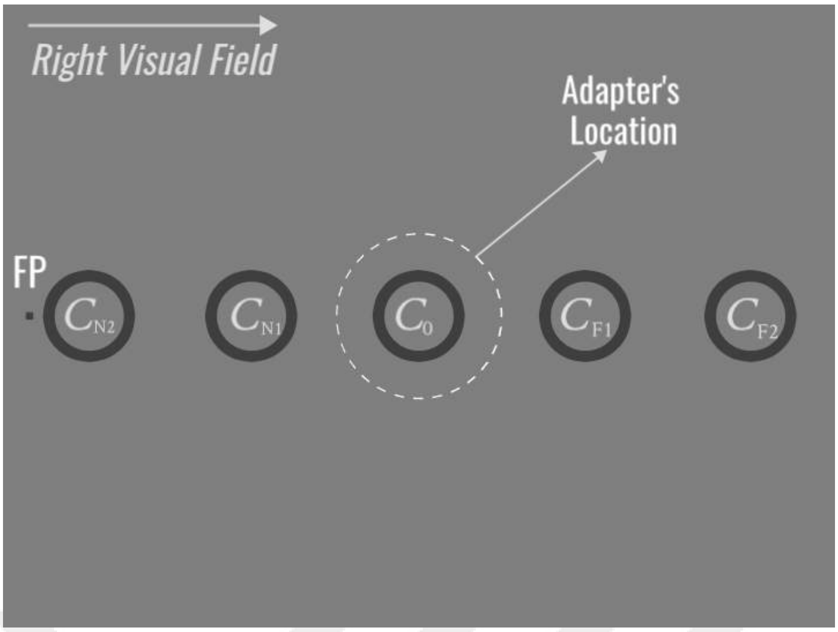

Figure 4.1: Spatial layout for all positions tested in Experiment III. Five positions of small reference stimuli in the right visual field were shown with dark gray circles. White dashed circle shows the adapter's location. One reference annulus was presented at a time, in the test phase of each trial, accompanied by its corresponding variable stimulus on the other visual field (not shown here for simplicity). FP: fixation point, C: center, N2: nearer 2, N1: nearer 1, 0: zero, F1: further 1, F2: further 2.

4.2. Results

4.2.1. Small Test Size

On average of the left and the right visual fields, small reference rings at the C_0 position were perceived 40 ($\pm$2.1 *SEM*)% smaller in the adaptation condition as compared to those in the control condition. Similarly, reference rings at all of the 4 eccentric positions were also perceived smaller in the adaptation condition (Figure 4.2 A).

Paired t-tests revealed significant difference between the adaptation and control conditions, in terms of the percent changes in perceived size of reference rings, in all of the five test positions (FDR corrected ps < 0.001).

A two-way repeated measures ANOVA was performed. Dependent variable was

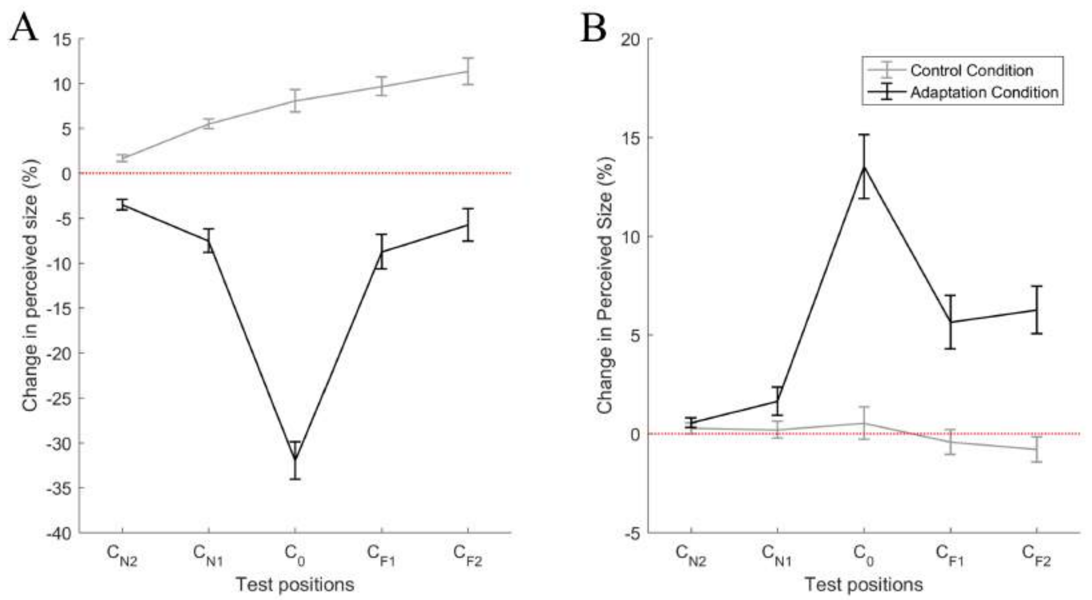

Figure 4.2: Results of Experiment III. Figure illustrates percent change in perceived size (y-axes) as a function of test positions (x-axes) for small (A) and large (B) reference ring conditions. Positive and negative values in y-axes represent perceptually larger and smaller rings, respectively. Control conditions were shown with gray line, adaptation conditions were shown with black line. Error bars: standard error. C: center, N2: nearer 2, N1: nearer 1, 0: zero, F1: further 1, F2: further 2.

adaptation index; independent variables were adapter region (with 2 levels: left and right) and reference ring position (with 5 levels: N2, N1, 0, F1, F2). Results showed that there was a significant main effect of test position ($F(4, 44) = 98.88$, $p < 0.001$). There was no significant main effect of adapter region, and no significant interaction between the adapter region and test position (respectively, $F(1, 11) = 1.1371$, $p = 0.31$; $F(4, 44) = 1.46$, $p = 0.23$).

Post hoc comparisons for test positions showed that the zero position was significantly different from all other (i.e. eccentric) positions (Bonferroni corrected ps < 0.001). In addition, N2 position was also significantly different from all other positions (Bonferroni corrected ps < 0.001). Details of the paired t tests and the post hoc comparisons can be found in Appendix B.3.

4.2.2. Large Test Size

Perceived sizes of the large reference rings at the C_0 position were 13 (± 1.8 *SEM*)% larger in the adaptation condition than those in the control condition. This perceptual effect of overestimation was also found at other test locations with smaller percent changes (see Figure 4.2 B).

Five paired *t*-tests were performed to compare adaptation and control conditions. Results showed that the perceived sizes of the adaptation conditions were significantly larger than those of the control conditions, at three of the five positions: 0, F1, and F2 (ps < 0.001). Multiple comparisons were corrected with FDR.

A repeated measures ANOVA was performed with the same factors used in the small test size analysis. Since Mauchly's test of sphericity indicated a significant violation of the sphericity assumption ($p < 0.05$) for the test position factor, degrees of freedom was corrected via Greenhouse-Geisser correction. A significant main effect of test position was found (sphericity corrected; $F(1.99, 21.99) = 29.99$, $p < 0.001$). There was no significant main effect of adapter region and no significant interaction between adapter region and test position (respectively, $F(1, 11) = 4.39$, $p = 0.06$ and $F(2.62, 28.86) = 2.86$, $p = 0.06$).

Bonferroni corrected post hoc comparisons showed that the adaptation index at zero position was significantly different than the adaptation index at other positions at $p < 0.01$, except F2. Other comparisons were not mentioned here, but can be found in the relevant table in Appendix B.3

4.3. Discussion

In this experiment, we tested the effect of size adaptation with a different stimulus, ring (i.e. annulus), in five positions which were also tested with discs in the previous experiment. Results showed that the small (or larger) reference annuli were perceived even smaller (or larger) after being exposed to a mid-sized annulus adapter. This under- and overestimation of size was largest in the zero position (C_0) in which reference rings were concentric to the adapter.

Results supported the findings of the previously mentioned experiments, in respect to the non-local effect of size adaptation. Different from the previous experiment, the difference between the effect on the left and the right visual field was significant for neither of the annulus sizes.

More importantly, illusion magnitudes found in the present experiment were highly similar to those found in the center positions of the previous experiment, meaning that the adaptation effect survives despite the absence of inner stimulation. Table 4.1 shows the adaptation index values for annuli at each position tested in the current experiment, together with those for discs at center row in the previous experiment.

Table 4.1: Comparison of two stimuli in terms of mean adaptation index (%)

	C_{N2}	C_{N1}	C_0	C_{F1}	C_{F1}
Disc (S)	-4.25 (0.75)	-9.29 (1.21)	-35.36 (2.09)	-9.62 (1.49)	-10.99 (2.78)
Annulus (S)	-5.16 (0.70)	-13.01 (1.34)	-40.04 (2.11)	-18.41 (1.77)	-17.08 (1.88)
Disc (L)	0.23 (0.52)	1.93 (0.65)	12.06 (1.67)	6.56 (1.03)	6.54 (1.39)
Annulus (L)	0.28 (0.47)	1.44 (0.86)	12.99 (1.79)	6.06 (0.97)	7.05 (1.23)

Note 1. S: small, L: large.
Note 2. ± SEM stated in parantheses.

We performed a mixed ANOVA to compare the adaptation index with disc and with annulus, and found that the effect for small test size was even stronger with annulus (significant main effect of stimulus type; $F(1,22) = 10.25$, $p = 0.004$). However, when taking the test positions into account, there was no significant interaction effect between the positions and the stimulus type (sphericity corrected; $F(2.38, 52.3) = 1.85$, $p = 0.16$). As for the large test size, we performed the same statistical analyses and found that there was no significant difference between the two stimuli, in terms of adaptation index (no significant main effect of stimulus type; $F(1, 22) = 0.008$, $p = 0.93$); and no significant interaction between the positions and the stimulus type (spericity corrected; $F(2.34, 51.55) = 0.22$, $p = 0.84$).

Results of this experiment suggests that the adaptation effect we found is independent of the stimulation of the inner parts of the adapter stimulus. This also suggests that the edges of the stimulus is enough for the size aftereffect.

CHAPTER 5

GENERAL DISCUSSION

The main purpose of the present study was to find out the spatial extent of distortions in the perceived size, after adapting to a size. Previous research has reported the size adaptation effect only at the exact position of the adapter stimulus, which corresponds to the same retinal location (e.g. Pooresmaeili et al., 2013; Kreutzer, Fink, & Weidner, 2015; Zeng, Kreutzer, Fink, & Weidner, 2017; Zimmermann & Fink, 2016). However, whether the size aftereffect is spatially limited to the adapter's location has yet to be reported. In order to address this gap in the literature, we investigated the bidirectional shifts in the perceived size at various peripheral locations, as a result of the prolonged exposure to a peripheral adapter stimulus of a certain size and a certain location.

In the first experiment, we measured the size adaptation effect on two sizes of test discs at five different locations: one concentric and four eccentric to the adapter. In line with the previous research, the results showed that adapting to a mid-sized disc caused subsequently presented small disc to be perceived even smaller, and large disc to appear even larger than veridical. More importantly, results revealed that the adaptation effect was observed substantially at the eccentric locations, too. In detail, there was an adaptation effect at 4° further from the adapter disc. In the second experiment, the effect of the same adapter stimulus was tested in 15 different positions in total, which covers a wide range of area in the visual field.

Results of the second experiment showed that there was a considerable adaptation effect even at 8° away from the adapter, meaning that the spatial extent of the size aftereffect was even broader than that found in the first experiment. We have also mapped the overall distortion in the perceived size, caused by the adapter disc. The pattern of the size aftereffect showed that the perceptual distortion was maximum at the concentric location, and decreases at the eccentric locations. In the last experiment, the adaptation effect was tested in five positions with ring stimuli instead of the disc. The adaptation effect was again observed at the concentric and the eccentric positions. Besides, the magnitude of the perceptual effect was almost the same as that with the disc stimuli. This shows that the stimulation of the inner parts of the circular adapter stimulus did not have a considerable role in the size aftereffect, highlighting the priority of stimulus edges on size adaptation. Overall, these findings suggest that the size adaptation is not location-specific, instead, it has a broad area of influence.

The alterations in the perceived size after adaptation might be related to the receptive field (RF) properties of neurons. Previous studies have shown that the V1 neurons can shift the position of their receptive fields [RFs] in response to the contextual influences on perceived size (Ni, Murray, & Horwitz, 2014; He, Mo, Wang, & Fang, 2015). The hypothesis is that the positions of RFs shift towards the center of the perceptually larger ring so that the total number of activated neuron for that ring increases; and also that the RF positions shift outwards for the perceptually smaller ring, leaving a less amount of activated region for that particular ring. Considering our results for the ring stimuli, although only the edges were present, the adaptation effect was still observed substantially. Therefore, the RF position-shift model can account for the adaptation effect at the concentric position, if the positions of RFs shift towards the edges (not towards the inner parts) of the adapter stimulus, from both inner and outer areas of the adapter. However, this kind of RF position-shift mechanism cannot explain the entire results, because according to such a low-level model we would expect to see the adaptation effect only at the adapted location, and we would expect to see either no adaptation effect or sometimes even a reversal of the effect at eccentric positions.

There are few studies showing evidence about the adaptation effect at non-stimulated retinal location (Suzuki & Cavanagh, 1998; Zimmermann, Weidner, Abdollahi, & Fink, 2016), but there is no study to our knowledge, reporting the eccentric size adaptation effect. The underlying mechanism of this eccentric size aftereffect which we found in the current study is not known yet, however this spread of the effect might be due to a global decrease in the size sensitivity of neurons within multiple layers of the visual hierarchy. This possibility is in line with the fMRI results of Pooresmaeili et al. (2013). They found change in the activated area in multiple visual areas: V1, V2, V3 and V4 (activation change in V4 was not significant but was in the same direction), in response to the perceived size, after adaptation. If the adaptation-induced shift in perceived size is resulting from the overall decreased sensitivity in multiple areas, then the eccentric areas might be influenced by the decreased sensitivity of higher level areas, due to their relatively large receptive field size. This would also explain the relatively weaker adaptation effect at eccentric locations.

In all three experiments, we tested the size adaptation effect for two test sizes: smaller and larger than the adapter stimulus. When considering the mean adaptation index values (mean of left and right visual fields), sizes of the small reference stimuli were underestimated at all positions, and the sizes of large reference stimuli were overestimated at most of the positions. The direction of the adaptation effect was consistent across experiments. However, there was an asymmetry between the magnitude of overestimation and the magnitude of underestimation. While there was strong underestimation in every test position, there was relatively less overestimation effect. In some locations the magnitude of overestimation was not even significant. A similar asymmetry was also present in the previous size adaptation studies (Pooresmaeili et al., 2013), as well as other studies on illusory size perception (Schwarzkopf & Rees, 2013).

Such an asymmetry in the direction of the perceptual effect is reasonable, given that the strength of the signal coming from the small and the large reference stimuli would not be the same. Suzuki and Cavanagh (1998) have tested the shape aftereffect with various levels of signal strength of test stimulus, by means of varying duration, eccentricity and luminance contrast of the test stimulus. They have shown, in two of their experiments, that the magnitude of the shape aftereffect was decreased with low luminance, with large eccentricity and with long test duration. Their findings supported the idea that when the available signal of the test stimulus is abundant, the perceived test stimulus becomes less prone to be distorted by a previous adapter stimulus. In light of these findings, it is plausible to consider a larger sized disc as a source of stronger signal strength. Thus, the weaker adaptation effect on the large test stimuli (as compared to the effect on the small test stimuli) in our study is likely to be due to the higher amount of image signal reaching to the visual system, which possibly makes easier to correct the biased perception.

Since this hypothesis predicts less illusory effect as the information gathered into the visual system increases, such correction hypothesis also helps to account for the relatively lower magnitude of size aftereffect at the locations near fixation point (e.g. weaker size aftereffect in nearer 2 and nearer 1 positions in Experiment II and III). It has been shown that the density of ganglion cells decreases as the eccentricity increases (Wässle, Grünert, Röhrenbeck, & Boycott, 1990), and thus, the visual field is not being mapped uniformly. Visual sensitivity is maximum near the fovea and it decreases as the eccentricity increases (e.g. Rijsdijk, Kroon, & van der Wildt, 1980). Therefore, one interpretation for the low adaptation effect near fixation point might be related to the high image sampling density near the fovea, as would be predicted by the correction hypothesis. Alternatively, there might have been a shift in the participant's strategy for those test stimuli at nearer locations. In the test phase, the distance between the fixation point and the center points of the two test stimuli was always the same. However, the edge-to-edge distances to the fixation point varied in connection with the changing size of variable stimulus. This variation in the edge-to-edge distance might have provided an additional cue. Although the participants were told to compare nothing but the sizes of the two test discs, they might have used the distance information for the near locations, without being aware of it.

In this present study, there were control conditions in which participants compared sizes of two circular stimuli without any manipulation to the perceived size. With the help of control conditions, we were able to correct possible biases in the adaptation conditions, and also to measure the perceived size irrespective of the adaptation effect. Despite no statistical analyses were performed specifically for the control conditions, a great majority of the participants surprisingly showed a small bias towards perceiving the reference stimulus larger than the veridical. This overestimation pattern in the control conditions was observed in all experiments and regardless of the visual field in which the reference stimulus presented. The only difference between the reference stimulus and the variable stimulus was that the reference stimulus had a fixed size throughout the session. None of the participants was aware of the one having the constant size, because the test discs were presented randomly in five different locations. Yet, being unaware of that does not eliminate the possibility of directing the attention particularly to one of the discs. In any case, however, the same overestimation bias should be relevant for the adaptation conditions as well. It is unlikely that the adaptation condition remain free from bias. Hence, we eliminated that possible bias in the adaptation condition by subtracting the control condition from it.

Unlike the previous studies on size adaptation (e.g. Pooresmaeili et al., 2013; Zimmermann, Morrone, & Burr, 2016; Zeng et al., 2017), here the adaptation effect was tested in both left and right visual fields in separate sessions. Interestingly, when comparing the adaptation effect in the two visual fields, there was an asymmetry in the perceptual effect. The difference between the visual fields was not consistently significant in all experiments, meaning that the difference might not show a robust effect, but the data shows that the adaptation effect was mainly stronger in the left visual field. If there is such a tendency, this asymmetry might predict hemispheric lateralization of visual size judgments. However, previous research showed conflicting results on the lateralization of size illusions. Corballis, Funnell, and Gazzaniga (2002) have found that the size discrimination is more accurate in the left visual field, implying that the perceived size should be less susceptible to illusory shifts in the left visual field. In line with this prediction, Saneyoshi (2018) reported that the small Ebbinghaus inducers created greater perceptual overestimation of size when presented in the right visual field. On the contrary, Muller-Lyer illusion has been found to produce a stronger perceptual effect in left visual field (Clem & Pollack, 1975).

As an alternative explanation, the adapter stimulus might have served as an attentional cue when presented in the left visual field (Anton-Erxleben et al., 2007; Gobell & Carrasco, 2005), because of the lateralization in visuospatial attention (De Schotten et al., 2011). Nevertheless, it is more likely that the asymmetry caused by the unique combination of all features of the stimuli such as eccentricity, luminance, exposure duration, together with the attentional lateralization, since it has been proposed that the hemispheric superiority depends on the complex interaction between features of visual input (Sergent, 1983).

The other noteworthy finding of the current study is that we have observed a bidirectional effect of size adaptation, that is, the adapter caused both perceptual underestimation and overestimation of size, depending on the test size. Previous studies on adaptation has reported that the direction of adaptation depends on the stimulus presentation (Hata & Motoyoshi, 2018; Sun, Kingdom, & Baker, 2017). Sun et al. (2017) has reported that the texture (i.e. density) adaptation is bidirectional when the two test stimuli (test and match, as they named) were presented sequentially, but unidirectional when presented simultaneously. For the simultaneous presentation, there was only perceived underestimation. One argument they have proposed as an explanation was that the larger receptive fields may take part in for sparser densities, which possibly lead adapter to affect the perceived density of both test stimuli when the two presented simultaneously, so that the bidirectionality could not be observed. In the current study, the two test discs were simultaneously presented, and there is possibility for adapter to affect both test stimuli given the effect was spreading. Despite this, we found strong bidirectional size aftereffect. If the adapter stimulus influenced both of the test stimuli, including the one presented at the other visual field, this means that the real magnitude of the aftereffect would be even larger, in terms of both the magnitude and the spatial extent, than we have found.

Briefly stated, our results demonstrated that the temporal context alters the size perception within a wide spatial extent. We found that the perception of an object depends on another object, although neither the presentation time nor the location was in common between the two. This suggests that the visual perception is the outcome of a dynamic process in which the temporal information and spatial information are being integrated and that the subsequent perception is being influenced by the combination of the two aspects of information. Additionally, these findings may have further implications on how the visual system encodes the information, how it maximizes the efficiency and how it adjusts the visual input. As also proposed by previous studies, adaptation may have several favorable consequences for the visual system: It may lead an improvement in the ability to discriminate certain features of a stimulus (Greenlee & Heitger, 1988), help to point out the novelties in the visual scene (McDermott, Malkoc, Mulligan, & Webster, 2010), and serve as a gain control system to maximize efficiency (Wainwright, 1999; Barlow, 1990). Together with the findings of the present study, we can posit that these type of consequences of adaptation are also not limited to the adapter's exact location.

5.1. Future Directions

The aforementioned perceptual bidirectionality in the aftereffect was also predicted by the channel model (Blakemore & Sutton, 1969; Blakemore et al., 1970; Suzuki &

Cavanagh, 1998). The model explains the adaptation effect at concentric location to a large extent, but since it is based on local size tuning properties, remains inadequate to explain the effect at eccentric, non-stimulated locations (The lack of spatial aspects in this model of size-tuning mechanism has also been criticized in Gelb & Wilson, 1983). Thus, a comprehensive model which could also predict the adaptation effect at eccentric areas can be formulated in a future work.

In addition, an fMRI study is needed further to reveal the neural correlates of the size adaptation effect, and its spatial extent. Pooresmaeili et al. (2013) has shown that the spatial extent of the activated area in V1 matched with the perceived size after adaptation. Small cortical area was activated for perceptually smaller stimuli, and vice versa. In light of the previous fMRI findings and the current findings, whether the same pattern of activation can also be found for the eccentric locations should be studied in order to figure out the mechanisms involved in the size adaptation. Also, an fMRI study would allow to investigate the interhemispheric interactions possibly involved in the processing of the size adaptation. Such a study would also reveal whether the adapter stimulus in our study has an influence on the perceived size of the variable stimuli as well as that of the reference stimuli.

Lastly, it is most likely that such a global spatial spread of the adaptation effect is also pertinent for other visual adaptations, given the similar nature of size adaptation and other adaptations (Webster, 2011, 2012). Therefore, future work can test the adaptation to many other stimulus dimensions at eccentric locations, such as adaptation to orientation (i.e. tilt), motion and facial expression.

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APPENDICES

APPENDIX A. PILOT STUDIES

A.1. Pilot I: The size aftereffect magnitude as a function of varying test disc sizes (two adapters)

Previous studies have reported bidirectional perceptual effect of size adaptation (e.g. Pooresmaeili et al., 2013). The direction of the perceptual effect depends on the relative size of test stimuli and the adapter stimulus. After being adapted to a large adapter stimulus, subsequent smaller test disc was perceived even smaller, and vice versa. Therefore, the magnitude of the perceptual effect is likely to be affected by the ratio between the sizes of the adapter and the test stimuli. In this pilot study, various sizes of test stimuli were used to test the perceptual effect after adapting to a certain-sized adapter stimuli.

A.1.1. Method

A.1.1.1. Participants, Stimuli and Apparatus

The author was the only participant of this pilot study. Stimuli were generated and presented via MATLAB (Mathworks) PsychToolbox (Brainard, 1997). Subject was seated in front of a 15.6-inch screen (Lenovo ideapad 510-15ISK; 60 Hz refresh rate; 1920 × 1080 screen resolution) with a viewing distance of approximately 50 cm.

An instruction display was shown before the experiment. Participant proceeded to the experimental trials by a key press. Figure A.1 shows the time sequence of events. Each trial consisted of two phases: An adaptation phase and a test phase. Two phases were separated by a 300 ms uniform mid-gray display. Durations of each phase and blank were adopted from Pooresmaeili et al. (2013).

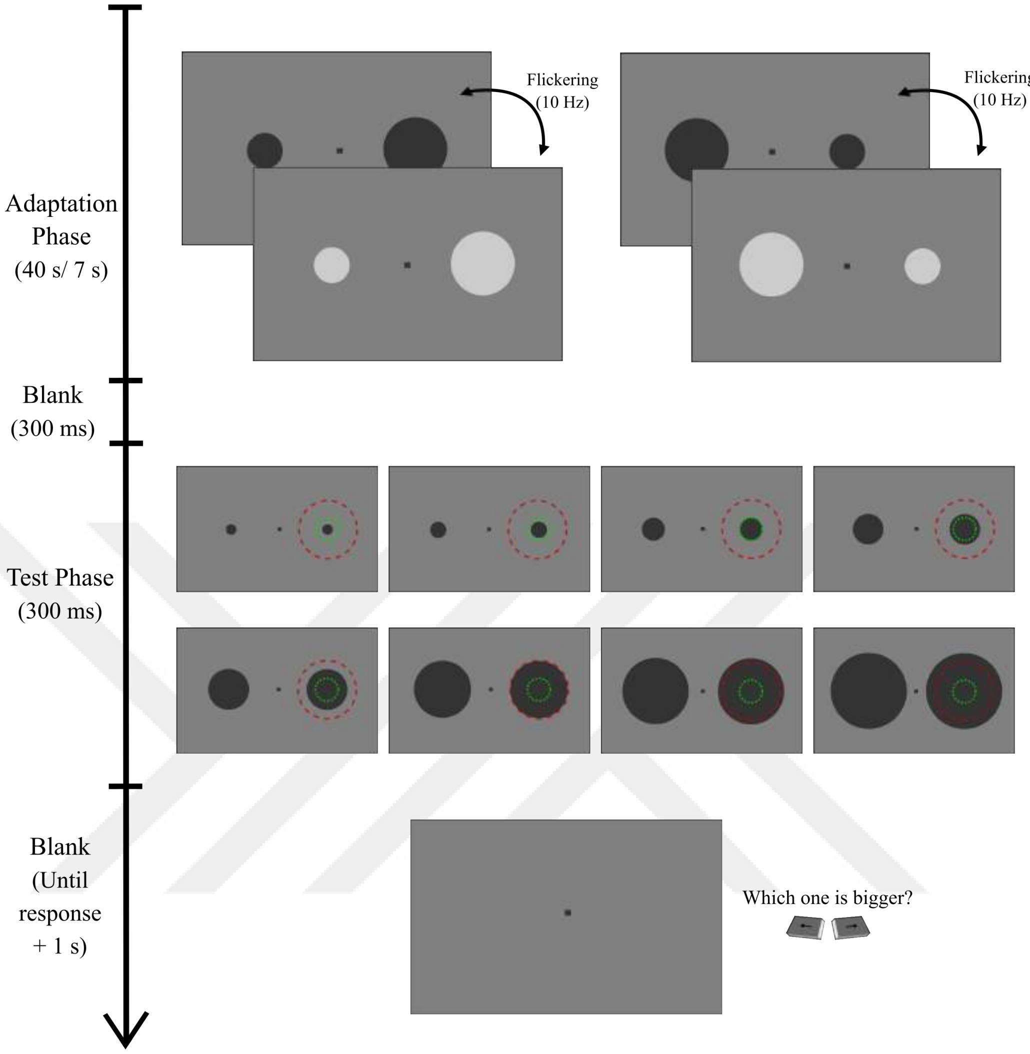

Figure A.1: Time sequence of events in a single trial of first pilot study. Trials started with an adaptation phase in which two flickering adapter discs were presented at both visual fields. The one on the right visual field was either large or small, and respectively, the one on the left visual field was either small or large. Following the adaptation phase, a blank screen with a fixation point was presented for 300 ms. In the test phase, there were two discs at both visual fields: Reference disc was always at the right visual field, and the variable disc was always at the left visual field. 8 different reference disc sizes were tested in separate sessions. Red and green dashed circles respectively represent the large and the small adapter disc preceding the reference disc. Test phase lasted 300 ms and followed by a blank screen while the participant was required to press one of the allowed keys to indicate the bigger disc in the test phase. The blank fixation screen remained until 1 second after participant responded.

Adaptation: Adaptation display consisted of two adapter discs. The discs were located at ≈10° to the left and ≈10° to the right of the fixation point. Adaptation phase lasted 40 seconds in the first trial as initial adaptation; and 7 seconds later on, as top-up adaptation. Adapter discs were flickering at 10 Hz from dark gray to light gray in order to prevent afterimages. Sizes of the left and the right adapters were either 80 pixels (≈1.6°) and 160 pixels (≈3.3°); or 160 pixels and 80 pixels, subsequently. The adapter sizes remained the same throughout a session.

Test: Test phase appeared after a short display of gray background presented in between the two phases. It consisted of two test discs: (1) a reference disc which has stable size throughout a session, and (2) a variable disc whose size was varied as it was subjected to one-up one-down interleaved staircases. The reference disc was always located at the right visual field, and the variable disc was always at the left visual field. Both test discs were presented at the same location as the adapters (≈10° away from the fixation point). Color of test discs was dark gray. Test phase lasted 300 ms. 8 sizes of reference disc were used in different sessions. These sizes were equally spaced between 40 (≈0.8°) and 200 (≈4°) pixels. See the test phase in Figure A.1

Followed by the adaptation and the test phases, participant was required to give response to proceed to trials. Mid-gray background was presented until the subject presses one of the allowed keys.

A.1.1.2. Procedure and Data Analysis

There were 18 sessions in total: 2 adapter pairs × 9 sizes of reference disc. The observer's task was to indicate the bigger test disc using left or right arrow keys of the keyboard while maintaining gaze on the fixation point which was at the center of screen. Adaptive staircase procedure was used to measure the perceived size of the reference disc. Using two separate staircases, the size of variable disc was updated after each trial, depending on the response of the participant. If the participant's response indicate the variable disc as bigger than the reference disc, then the variable disc's size got smaller; and if otherwise, the variable disc's size got larger in the next trial of the same staircase. Step size was 32 pixels (0.66°) at the beginning but decreased by half after each reversal until it reached to 4 pixels (0.08°). Sessions consisted of 50 trials (2 staircases $\times$ 25 trials) in total. The number of trials in a staircase was carefully decided by testing. Staircases were presented in a random order, however the maximum number of consecutive selection of the same staircase was limited to 3. In other words, the same staircase was not presented 4 times consecutively.

After each session, data were fitted with a logistic function using Psignifit 4 MATLAB Toolbox (Schütt et al., 2016). Lapse and guess rates were fixed to 0.01 and overdispersion parameter was kept free.

Points of subjective equality (PSE) were gathered from the fitted functions. The percent change between the actual size and the perceived sizes (also called percent adaptation effect), was calculated for each of the 18 PSE values, in order to have a better understanding of the magnitude of the size illusion.

A.1.2. Results and Discussion

Percent adaptation effect for each measurement were plotted as a function of the test-adapter size ratio in Figure A.2. Since the perceived size of reference disc was measured, the adapter preceding the reference disc was used in the size ratio calculations.

Plots illustrate that the magnitude of size adaptation effect varied as a function of the size ratio, for both adapter pairings (left and right panels in the figure). When the reference disc was smaller than its preceding adapter, the size ratio was less than 1 (x-axes in the figure), and thus, was perceived even smaller (panel A in the figure) than veridical. Similarly, when the reference disc was larger than the preceding adapter disc, the ratio was greater than 1 and it was perceived even larger than it actually is (panel B).

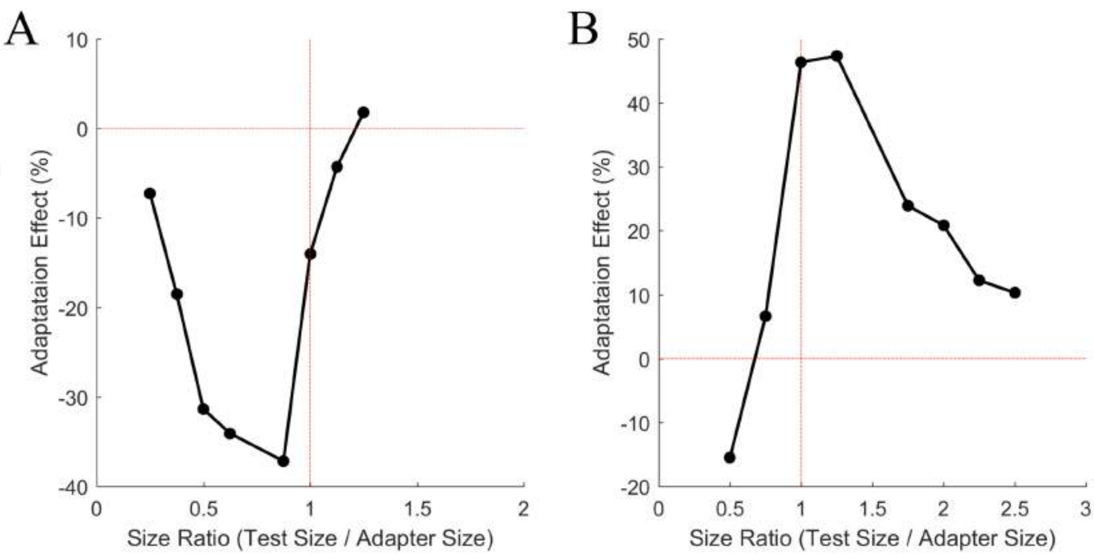

Figure A.2: Results of the first pilot study. y-axes represent the percent adaptation effect, and x-axes represent the size ratio of reference disc and adapter. The left panel (A) shows the graph for the sessions in which the reference disc was preceded by 160 pixels adapter disc on the right visual field. The right panel (B) shows the adaptation effect for the sessions in which the 80 pixels adapter was on the right visual field, preceding the reference disc. Positive values in the y-axes mean that reference disc was perceived larger than its actual size, while negative values indicate the opposite.

However, for the exact size ratio of 1, the adaptation effect was not as expected. Since there was no size difference between the preceding adapter disc and the test at the ratio of 1, there should not be any effect on the perceived size of the reference disc. For the 160 pixel sized test disc, the perceived size was underestimated more than 10 percent, when preceded by the adapter pair of 160 pixels on the left and 80 pixels on the right (panel A). Likewise, the 160 pixel sized test disc was perceived 45 percent larger than veridical when preceded by the second adapter pair (80 pixels on the left, 160 pixels on the right; panel B). This is possibly due to the existence of the adapter on the left visual field. It can alter the perceived size of the variable test stimulus and also the perceived size measurements.

So, findings of this study shows an evidence about the size adaptation effect, but does not provide a clear picture about the factor that causes the effect. Adaptation effect might be due to the right adapter's effect on reference disc, or due to the left adapter's effect on variable disc, or maybe and possibly, due to the interaction between both adapters and both test stimuli. This ambiguity discredits the validity of findings and thus, was eliminated in the second pilot study by using a single adapter disc at one of the visual fields at a time.

A.2. Pilot II: The size aftereffect magnitude as a function of varying test disc sizes (single adapter)

In the first pilot study we found varying magnitudes of adaptation effect on various sizes of test disc. However, in order to make sure that the PSEs are not influenced by the existence of another adapter on the other visual field, a further experiment with a single adapter disc was needed. In the second pilot study, there was one adapter stimulus preceding the reference disc. We aimed to find out the variations in the magnitude of adaptation effect on various sizes of test discs, using one adapter disc.

A.2.1. Method

A.2.1.1. Participants, Stimuli and Apparatus

The author participated in this pilot study. Stimuli were the same as the previous study, with a few exceptions. There was a single adapter disc located at the same location with the reference disc. The experimental design and the apparatus were also the same as of the first pilot study. The adaptation phase and the test phase were presented with a 300 ms separation.

Adaptation: In the adaptation phase, one flickering adapter was either on the left visual field or right visual field in separate sessions. Its size was 120 pixels ($\approx 2.5°$) and its center point was approximately 10° away from the fixation point. The duration was the same: 40 seconds for the initial adaptation, and 7 seconds for top-up adaptation.

Test: Two dark gray discs were presented in the test phase: a reference disc and a variable disc. Test phase duration was 300 ms. As in the previous pilot study, the variable disc and the reference disc were positioned $\approx 10°$ to the left and to the right of the fixation point. Reference disc was always presented at the same location as the adapter disc, with a constant size throughout the sessions. Variable disc's size was subject to one-up one-down interleaved staircase procedure. In separate sessions, 9 sizes of reference disc were tested. These sizes were ranging from 40 ($\approx 0.8°$) to 200 ($\approx 4°$) pixels, just as in the first pilot study.

A.2.1.2. Procedure and Data Analysis

After the test phase display, mid-gray background was presented until the participant pressed either right or left arrow key to indicate bigger test disc. Based on the participant's response, variable disc's size changed in the subsequent trial throughout the session. One-up one-down two interleaved adaptive staircases were used for the size of variable disc. Step size varied as in the first pilot study.

There were 18 sessions in total: 2 adapter region (left and right visual fields) × 9 sizes of reference disc. Each session consisted of 50 trials (2 staircase × 25 trials) for a single reference disc size at one visual field. The order of two staircase was randomized but the same staircase could not be selected four times consecutively. However, sessions were not randomized.

Data from each session were fitted into logistic function using Psignifit 4 (Schütt et al., 2016), with the same parameter specifications as the previous pilot study. The PSE values and the percent adaptation effects were calculated for each reference disc size.

A.2.2. Results and Discussion

Results were shown in Figure A.3. In accordance with the literature, the adaptation effect was bidirectional, meaning that the perceived size of the reference disc was both overestimated and underestimated, depending on the reference disc size. In general, smaller reference discs (as compared to the adapter; see size ratio values between 0 and 1 in both graphs of Figure A.3) were perceived even smaller than veridical, larger reference discs (as compared to the adapter; see size ratio values between 1 and 2 in both graphs of Figure A.3) were perceived even larger than veridical in both visual fields.

As also shown in the figure, the adaptation effect does not follow a linear pattern of increment, as the size ratio between the reference disc and the adapter increases. Similar pattern of adaptation magnitude was also reported by Blakemore and Sutton (1969). This indicates that there is an optimum size ratio for the maximum adaptation effect.

In addition, results showed that the magnitude of adaptation effect was greater in the right visual field (panel B) as compared to that in the left visual field (panel A). The maximum adaptation effect for the large reference discs was around 5 percent in the left visual field and around 20 percent in the right visual field. Likewise, the

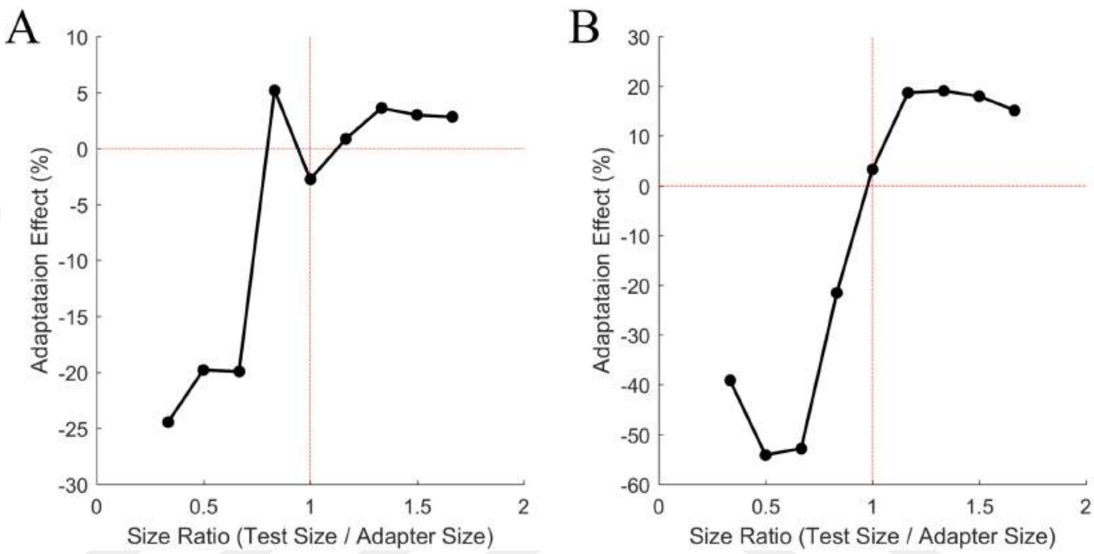

Figure A.3: Results of the second pilot study. Two graphs represent the percent adaptation effect as a function of the size ratio between the reference disc and the adapter disc. Left panel (A) illustrates the results of the sessions in which the adapter was presented on the left visual field, and similarly right panel (B) shows the results for the right adapter sessions. Positive values in y-axes represent perceptual overestimation, negative values represent perceptual underestimation of size. x-axes shows the ratio between sizes of the reference disc and the adapter. The ratios between 0 and 1 represent the reference discs smaller than the adapter, and values between 1 and 2 represents the larger reference discs. The ratio of 1 means no size difference between the reference disc and the adapter.

maximum adaptation effect for the small reference discs was around 25 percent in the left visual field, and around 55 percent in the right visual field. These values also show that the magnitude of the adaptation effect does not seem to be the same for both directions of the perceptual effect. The perceptual underestimation of size (for the small reference discs) was considerably stronger than the perceptual overestimation of size (for the large reference discs).

This experimental design, however, does not provide a complete answer to distinguish whether these asymmetries in the visual field and in the direction of the adaptation effect are due to the adaptation to size, or due to the size perception, independently of the adaptation. Therefore, an additional research was needed to investigate these asymmetries and the adaptation effect further.

A.3. Pilot III: The Adaptation Effect on Eccentric Test Discs

Previous pilot studies showed a non-linear relation between the magnitude of the size aftereffect and the size ratio between the reference disc and the adapter. Besides, several asymmetries in the perceived size of the reference disc, which are conceivably due to biases in the size perception, were found following a prolonged exposure to an adapter.

In the current study, we aimed to find out the pure effect of size adaptation, separately from any bias in the size perception. Therefore, we added control conditions in which the adaptation phase was absent. Moreover, unlike the previous pilot studies and the previous studies in the literature, the adaptation effect was tested at eccentric locations, too. The design of this study was mainly the same as the previous one, except that there were additional sessions for three eccentric positions of reference disc which were horizontally shifted versions of each other; and that there were additional sessions for control conditions for each test location and each reference disc size.

A.3.1. Method

A.3.1.1. Participants, Stimuli and Apparatus

The author was the only participant of this pilot study, too. Stimuli and durations of them were the same as the previous study with some exceptions. *Adaptation:* Adaptation phase was exactly the same as the previous study. Its size was always 120 pixels, and distance from the fixation point was 330 pixels (≈10°).

Test: Five different sizes of reference discs (40, 80, 120, 160, and 200 pixels) were tested in four different positions (3 eccentric and 1 concentric to the adapter). All reference disc positions were in the same horizontal axis as the adapter. The difference between the positions was their distance from the fixation point. Positions' distances from the fixation point were as follows: 130, 330, 450, 530 pixels. Given that the adapter was located 330 pixels away from the fixation point, the locations were named as nearer, center, further1 and further2 respectively. Similar to the previous pilot studies, reference disc had a fixed size while the variable disc's size was changing trial by trial. Also, variable disc's position was always symmetrical to reference disc with respect to the vertical center of the screen.

A.3.1.2. Procedure and Data Analysis

Similar to the previous pilot studies, participant was required to select the bigger test disc using arrow keys. Two adaptive interleaved staircases were used in each session. In the control (no-adaptation) conditions, there were only the test phase and the blank for the response period; but in the adaptation conditions, adaptation phase was presented as usual.

Each test position and each of the five reference disc sizes were presented in separate sessions. Every size and position combination was tested in both visual fields (left and right). So, there were 40 sessions (5 reference disc sizes × 4 positions × 2 visual fields) for adaptation condition and 40 session for control condition.

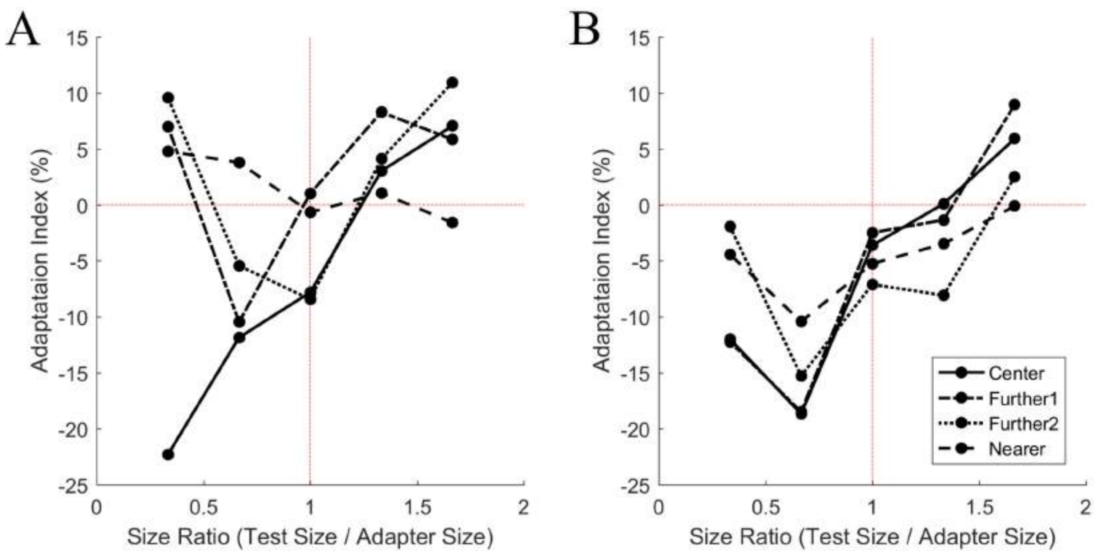

Figure A.4: Results of the third pilot study. Adaptation index values were plotted as a function of the size ratio between the reference disc and the adapter, for left (A; left panel) and right (B; right panel) visual fields. y-axes represent percent adaptation index. Positive and negative adaptation index values respectively mean that the reference disc was perceived larger and smaller than veridical. In x-axes, size ratio values smaller than 1 represent smaller reference discs and values larger than 1 represent larger reference discs as compared to the adapter's size. Four different test disc positions were shown with different lines.

Sessions were not randomized.

At the end of each session, the points of subjective equality (PSEs) and the percent adaptation effect were calculated just as in the previous pilot studies. In order to eliminate possible biases of perceived size, the percent bias in the control conditions were subtracted from the percent adaptation effect in the adaptation conditions. Obtained values were named as adaptation index.

A.3.2. Results and Discussion

Figure A.4 shows the percent adaptation index values. Similar to the previous findings, results of this pilot study showed that the small reference discs which were presented at the same location as the adapter, were perceived even smaller. Likewise, large reference discs at the same location were perceived even larger after an adaptation to a mid-sized disc. See straight lines in Figure A.4 for the center position.

More importantly, results showed that the effect of size adaptation was present in the eccentric positions, too. Especially in the right visual field (panel B in the figure), the magnitudes of size adaptation at eccentric locations noticeably similar to those at the center location. In the left visual field, although the adaptation index for the large reference discs (ratio greater than 1) follows a more-or-less similar pattern at all locations, the adaptation index for the small reference disc are quite different. The small reference discs' sizes at eccentric locations were overestimated, while at the center it was repeatedly found to be underestimated.

These results overall suggest that the size adaptation was not only effective at the adapter's location, but also at the adapter's surrounding area, meaning that the size adaptation is not location-specific. This pilot study gave an insight about the size aftereffect and its spatial extent, but were not adequate to make a valid conclusion, due to the limitations such as lack of statistical analyses, insufficient number of participants and failure to secure controlled experimental settings. Nevertheless, pilot studies helped us to optimize the parameters and the experimental design for the main experiments.

APPENDIX B. STATISTICAL OUTPUTS

B.1. Experiment I

Table B.1: Paired Samples T-Tests - Adaptation vs Control

			t	df	p_{FDR} *	Mean difference	SE difference
Cont_S_U	-	Adp_S_U	7.061277	11	1.1608e-5	11.7141	1.6589
Cont_S_N	-	Adp_S_N	12.203658	11	1.2225e-7	9.8832	0.8099
Cont_S_C	-	Adp_S_C	16.260301	11	1.2000e-8	38.3975	2.3614
Cont_S_D	-	Adp_S_D	9.462999	11	1.0665e-6	10.5906	1.1192
Cont_S_F	-	Adp_S_F	6.982628	11	1.1608e-5	15.2287	2.1809
Cont_L_U	-	Adp_L_U	-2.8864	11	0.0123	-2.6160	0.9063
Cont_L_N	-	Adp_L_N	-1.6706	11	0.0769	-1.1626	0.6960
Cont_L_C	-	Adp_L_C	-8.3613	11	1.0704e-5	-8.5900	1.0274
Cont_L_D	-	Adp_L_D	0.6844	11	0.7461	0.6679	0.9759
Cont_L_F	-	Adp_L_F	-4.2306	11	0.0018	-3.7885	0.8955

Note. Cont: control, Adp: adaptation, S: small, L: large, U: up, N: nearer, C: center, D: down, F: further.

* Corrected p values using a false discovery rate of 0.05.

Table B.2: Post Hoc Comparisons - Reference Disc Positions

		Mean difference	SE	t	p_{bonf}
S_C	S_N	-28.5143	2.4359	-11.7060	1.5004e-6
	S_F	-23.1688	3.5029	-6.6142	0.0004
	S_U	-26.6833	3.2223	-8.2808	4.6984e-5
	S_D	-27.8069	2.5617	-10.8548	3.2384e-6
S_N	S_F	5.3455	2.2301	2.3970	0.3542
	S_U	1.8309	1.9019	0.9627	1.0000
	S_D	0.7074	1.1386	0.6213	1.0000
S_F	S_U	-3.5146	1.0100	-3.4798	0.0515
	S_D	-4.6381	2.5978	-1.7854	1.0000
S_U	S_D	-1.1235	2.2008	-0.5105	1.0000
L_C	L_N	7.4273	1.5646	4.7471	0.0060
	L_F	4.8015	1.3112	3.6618	0.0374
	L_U	5.9739	1.6515	3.6173	0.0405
	L_D	9.2579	1.5136	6.1164	0.0008
L_N	L_F	-2.6258	1.2070	-2.1754	0.5228
	L_U	-1.4534	0.8735	-1.6638	1.0000
	L_D	1.8305	0.9743	1.8789	0.8700
L_F	L_U	1.1724	0.8698	1.3479	1.0000
	L_D	4.4563	0.9560	4.6614	0.0069
L_U	L_D	3.2839	0.9905	3.3153	0.0689

Note. S: small, L: large, U: up, N: nearer, C: center, D: down, F: further.

B.2. Experiment II

Table B.3: Paired Samples T-Tests - Adaptation vs Control

			t	df	p_{FDR} *	Mean Difference	SE Difference
Cont_S_U_{N2}	-	Adp_S_U_{N2}	2.1198	11	0.0332	3.2535	1.5348
Cont_S_U_{N1}	-	Adp_S_U_{N1}	2.0306	11	0.0360	5.3989	2.6588
Cont_S_U_0	-	Adp_S_U_0	5.4035	11	2.3143e-4	12.8044	2.3696
Cont_S_U_{F1}	-	Adp_S_U_{F1}	5.4772	11	2.3143e-4	11.4837	2.0967
Cont_S_U_{F2}	-	Adp_S_U_{F2}	5.5576	11	2.3143e-4	9.7316	1.7510
Cont_S_C_{N2}	-	Adp_S_C_{N2}	5.6974	11	2.3143e-4	4.2467	0.7454
Cont_S_C_{N1}	-	Adp_S_C_{N1}	7.6711	11	3.7500e-5	9.2910	1.2112
Cont_S_C_0	-	Adp_S_C_0	16.9036	11	2.4000e-8	35.3577	2.0917
Cont_S_C_{F1}	-	Adp_S_C_{F1}	6.4554	11	1.2000e-4	9.6164	1.4897
Cont_S_C_{F2}	-	Adp_S_C_{F2}	3.9600	11	0.0017	10.9913	2.7756
Cont_S_D_{N2}	-	Adp_S_D_{N2}	1.9086	11	0.0414	1.7827	0.9340
Cont_S_D_{N1}	-	Adp_S_D_{N1}	3.2394	11	0.0054	5.9032	1.8223
Cont_S_D_0	-	Adp_S_D_0	4.1174	11	0.0014	8.7637	2.1285
Cont_S_D_{F1}	-	Adp_S_D_{F1}	4.5722	11	7.5000e-4	11.2065	2.4510
Cont_S_D_{F2}	-	Adp_S_D_{F2}	2.9606	11	0.0081	7.2602	2.4523
Cont_L_U_{N2}	-	Adp_L_U_{N2}	2.1198	11	0.8460	3.2535	1.5348
Cont_L_U_{N1}	-	Adp_L_U_{N1}	2.0306	11	0.5368	5.3989	2.6588
Cont_L_U_0	-	Adp_L_U_0	5.4035	11	0.5368	12.8044	2.3696
Cont_L_U_{F1}	-	Adp_L_U_{F1}	5.4772	11	0.0933	11.4837	2.0967
Cont_L_U_{F2}	-	Adp_L_U_{F2}	5.5576	11	0.1754	9.7316	1.7510
Cont_L_C_{N2}	-	Adp_L_C_{N2}	5.6974	11	0.5368	4.2467	0.7454
Cont_L_C_{N1}	-	Adp_L_C_{N1}	7.6711	11	0.0242	9.2910	1.2112
Cont_L_C_0	-	Adp_L_C_0	16.9036	11	1.2000e-4	35.3577	2.0917

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Table B.3 (Cont'd)

			t	df	p_{FDR} *	Mean Difference	SE Difference
Cont_L_C_{F1}	-	Adp_L_C_{F1}	6.4554	11	2.0250e-4	9.6164	1.4897
Cont_L_C_{F2}	-	Adp_L_C_{F2}	3.9600	11	0.0016	10.9913	2.7756
Cont_L_D_{N2}	-	Adp_L_D_{N2}	1.9086	11	0.5368	1.7827	0.9340
Cont_L_D_{N1}	-	Adp_L_D_{N1}	3.2394	11	0.8460	5.9032	1.8223
Cont_L_D_0	-	Adp_L_D_0	4.1174	11	0.8460	8.7637	2.1285
Cont_L_D_{F1}	-	Adp_L_D_{F1}	4.5722	11	0.8460	11.2065	2.4510
Cont_L_D_{F2}	-	Adp_L_D_{F2}	2.9606	11	0.8460	7.2602	2.4523

Note. Cont: control, Adp: adaptation, S: small, L: large, U: up, C: center, D: down, N2: nearer 2, N1: nearer 1, 0: zero, F1: further 1, F2: further 2.

* Corrected p values using a false discovery rate of 0.05.

Table B.4: Post Hoc Comparisons - Reference Disc Positions

		Mean difference	SE	t	p_{bonf}
S_*0*	S_*N1*	-12.1108	2.3689	-5.1124	0.0001
	S_*F1*	-8.2064	2.3895	-3.4344	0.0154
	S_*N2*	-15.8810	2.2908	-6.9325	4.6694e-7
	S_*F2*	-9.6475	2.5403	-3.7978	0.0056
S_*N1*	S_*F1*	3.9045	1.3629	2.8648	0.0701
	S_*N2*	-3.7701	0.7824	-4.8189	0.0003
	S_*F2*	2.4633	1.2532	1.9655	0.5733
S_*F1*	S_*N2*	-7.6746	1.1301	-6.7912	7.1184e-7
	S_*F2*	-1.4412	1.4901	-0.9671	1.0000
S_*N2*	S_*F2*	6.2334	1.3317	4.6808	0.0004
L_*0*	L_*N1*	3.2534	1.0499	3.0988	0.0382
	L_*F1*	1.3136	0.7041	1.8655	0.7051
	L_*N2*	3.8830	1.1831	3.2821	0.0234
	L_*F2*	1.2393	0.8523	1.4541	1.0000
L_*N1*	L_*F1*	-1.9399	0.6293	-3.0828	0.0398
	L_*N2*	0.6295	0.4010	1.5700	1.0000
	L_*F2*	-2.0141	0.8198	-2.4570	0.1911
L_*F1*	L_*N2*	2.5694	0.7952	3.2311	0.0268
	L_*F2*	-0.0743	0.4891	-0.1518	1.0000
L_*N2*	L_*F2*	-2.6436	0.9042	-2.9237	0.0603

Note. S: small, L: large, *0*: zero, *N1*: nearer 1, *F1*: further 1, *N2*: nearer 2, *F2*: further 2.

B.3. Experiment III

Table B.5: Paired Samples T-Tests - Adaptation vs Control

			t	df	p_{FDR} *	Mean difference	SE difference
Cont_S_C_{N2}	-	Adp_S_C_{N2}	7.3448	11	7.2887e-6	5.1636	0.7030
Cont_S_C_{N1}	-	Adp_S_C_{N1}	9.7189	11	8.1850e-7	13.0087	1.3385
Cont_S_C_0	-	Adp_S_C_0	18.9876	11	2.5000e-9	40.0365	2.1086
Cont_S_C_{F1}	-	Adp_S_C_{F1}	10.4095	11	6.1800e-7	18.4066	1.7682
Cont_S_C_{F2}	-	Adp_S_C_{F2}	9.0686	11	1.2163e-6	17.0828	1.8837
Cont_L_C_{N2}	-	Adp_L_C_{N2}	-0.5966	11	0.2814	-0.2808	0.4706
Cont_L_C_{N1}	-	Adp_L_C_{N1}	-1.6823	11	0.0754	-1.4399	0.8559
Cont_L_C_0	-	Adp_L_C_0	-7.2776	11	3.9684e-5	-12.9869	1.7845
Cont_L_C_{F1}	-	Adp_L_C_{F1}	-6.2475	11	7.8528e-5	-6.0569	0.9695
Cont_L_C_{F2}	-	Adp_L_C_{F2}	-5.7097	11	1.1352e-4	-7.0474	1.2343

Note. Cont: control, Adp: adaptation, S: small, L: large, *C*: center, *N2*: nearer 2, *N1*: nearer 1, *0*: zero, *F1*: further 1, *F2*: further 2.

* Corrected p values using a false discovery rate of 0.05.

Table B.6: Post Hoc Comparisons - Reference Ring Positions

		Mean difference	SE	t	p_{bonf}
S_*0*	S_*N1*	-27.0278	1.6537	-16.3435	4.6053e-8
	S_*F1*	-21.6300	1.9051	-11.3538	2.0505e-6
	S_*N2*	-34.8729	2.2769	-15.3161	9.1486e-8
	S_*F2*	-22.9537	2.2508	-10.1979	6.0760e-6
S_*N1*	S_*F1*	5.3978	1.7996	2.9994	0.1209
	S_*N2*	-7.8451	1.1250	-6.9733	0.0002
	S_*F2*	4.0741	1.4958	2.7236	0.1980
S_*F1*	S_*N2*	-13.2429	1.7429	-7.5982	0.0001
	S_*F2*	-1.3238	2.2586	-0.5861	1.0000
S_*N2*	S_*F2*	11.9192	1.6019	7.4406	0.0001
L_*0*	L_*N1*	11.5470	1.4512	7.9569	6.8759e-5
	L_*F1*	6.9300	1.4948	4.6362	0.0072
	L_*N2*	12.7061	1.7989	7.0634	0.0002
	L_*F2*	5.9395	2.0164	2.9457	0.1331
L_*N1*	L_*F1*	-4.6170	0.7310	-6.3160	0.0006
	L_*N2*	1.1591	0.7444	1.5572	1.0000
	L_*F2*	-5.6075	1.2317	-4.5527	0.0083
L_*F1*	L_*N2*	5.7761	0.8582	6.7308	0.0003
	L_*F2*	-0.9905	0.9408	-1.0528	1.0000
L_*N2*	L_*F2*	-6.7666	1.1015	-6.1434	0.0007

Note. S: small, L: large, *0*: zero, *N1*: nearer 1, *F1*: further 1, *N2*: nearer 2, *F2*: further 2.

APPENDIX C. SUBJECT DATA

In the following 10 figures, results of each subject are shown for all three experiments. y-axes represent percent change in perceived size and x-axes represent test positions. Test positions were center, down, further, nearer and up for Experiment I; U_{N2}, U_{N1}, U_0, U_{F1}, U_{F2} for Experiment II - Up positions; C_{N2}, C_{N1}, C_0, C_{F1}, C_{F2} for Experiment II - Center positions; and D_{N2}, D_{N1}, D_0, D_{F1}, D_{F2} for Experiment II - Down positions. Test positions for Expeirment III were the same as those for Experiment II - Center positions. (N2: nearer 2, N1: nearer 1, 0: zero, F1: further 1, F2: further 2).

All data points in the figures are the average of the data for left and right visual fields. Positive values in y-axes means the perceived size was larger than veridical, and negative values means the opposite. Zero (shown with red dashed line) means that there is no difference between the perceived and the actual size of the reference stimulus. Control and adaptation conditions were shown with gray and black lines, respectively. Error bars show the standard error.

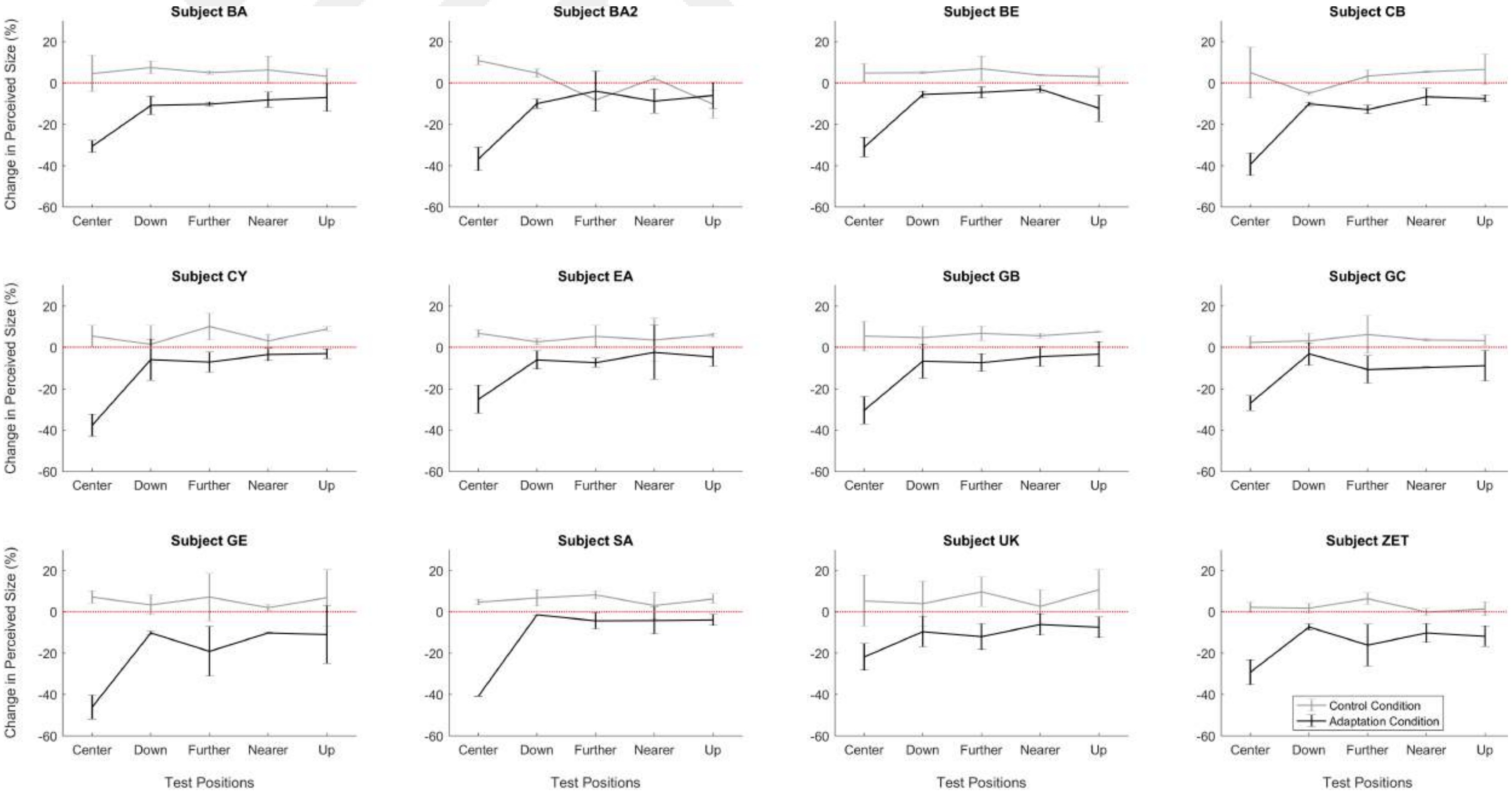

Figure C.5: Small reference disc results of Experiment I across subjects. See text in Appendix C for details.

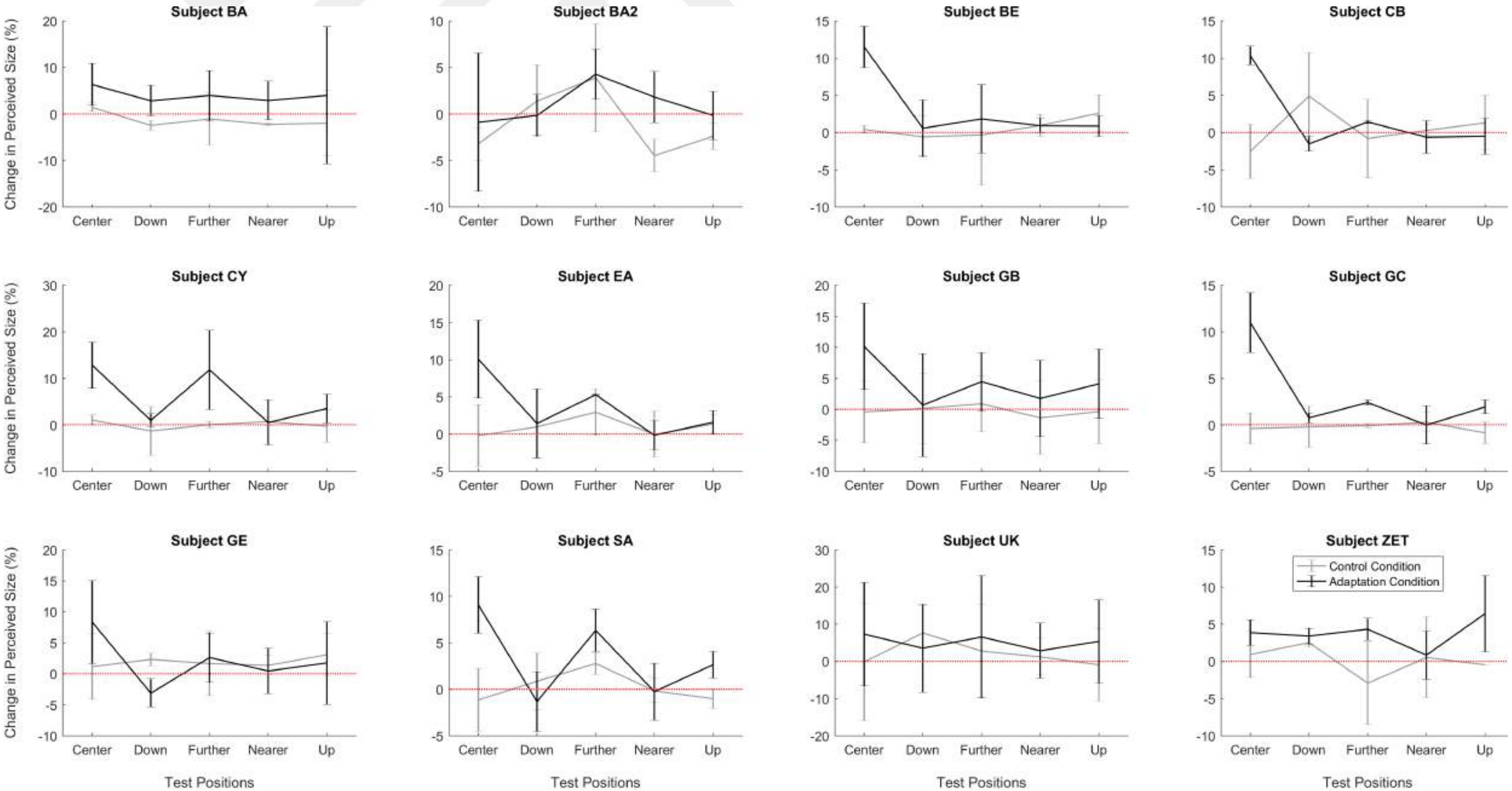

Figure C.6: Large reference disc results of Experiment I across subjects. See text in Appendix C for details.

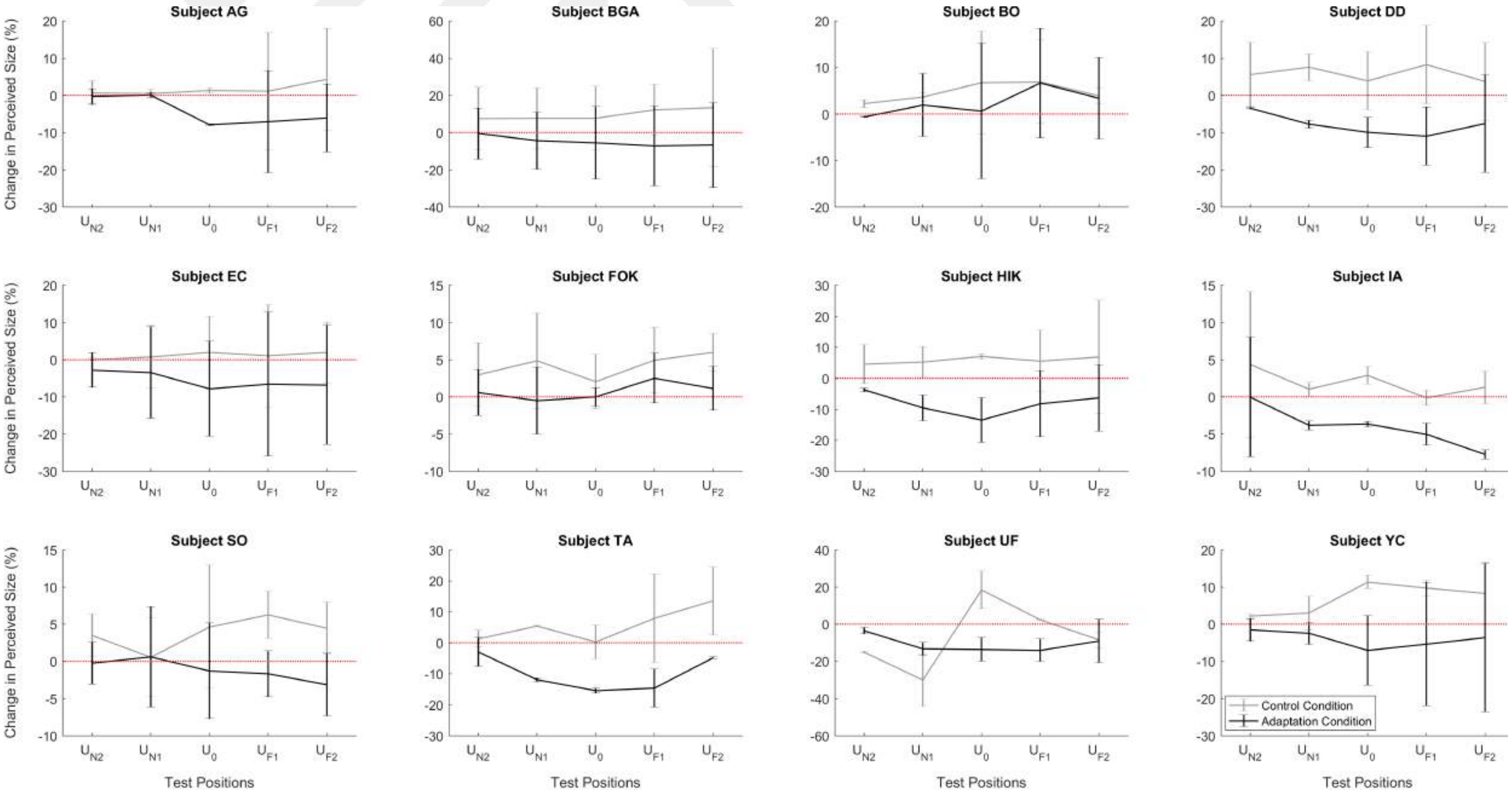

Figure C.7: Small reference disc results of Experiment II-Up positions across subjects. See text in Appendix C for details.

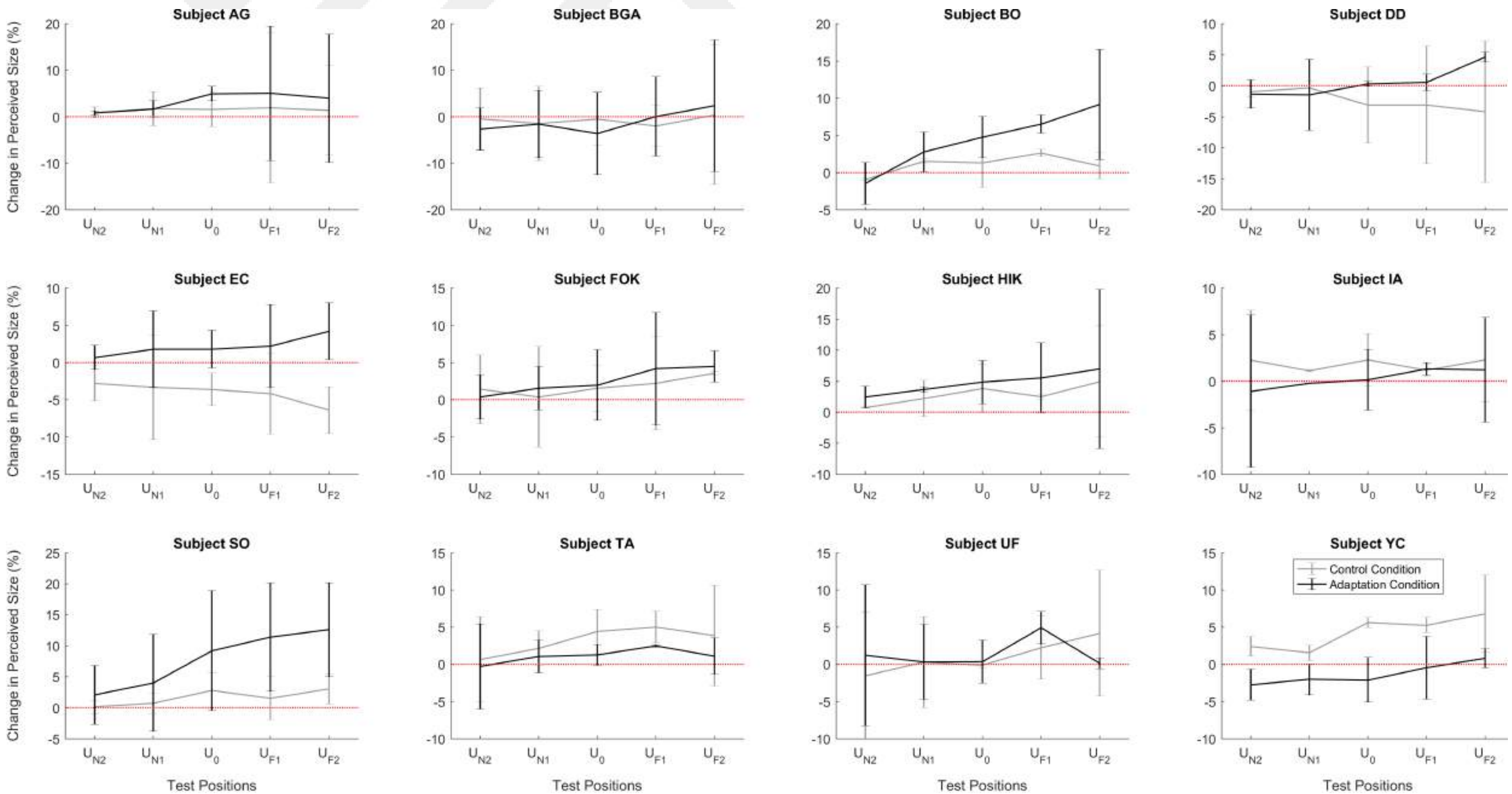

Figure C.8: Large reference disc results of Experiment II-Up positions across subjects. See text in Appendix C for details.

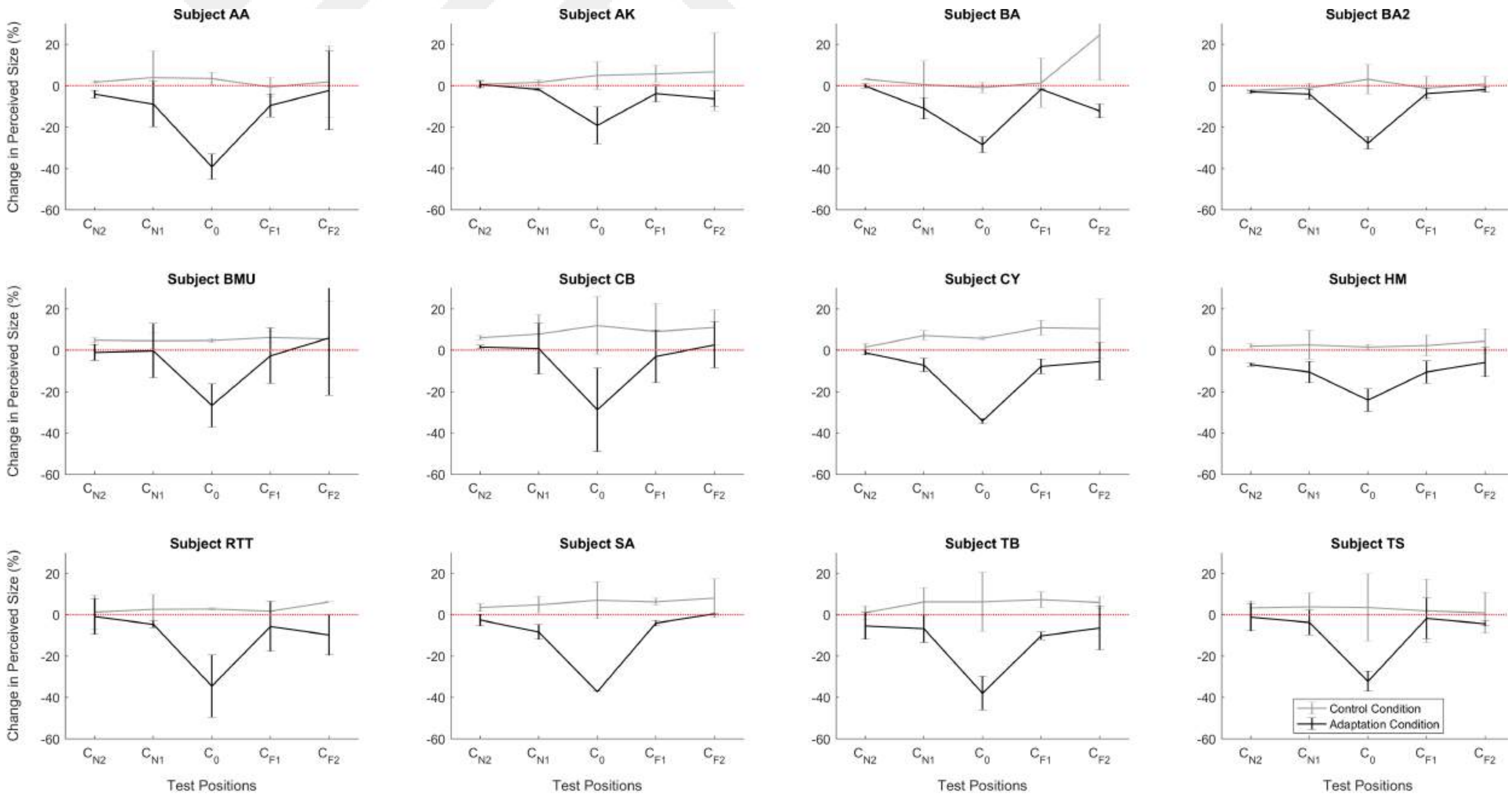

Figure C.9: Small reference disc results of Experiment II-Center positions across subjects. See text in Appendix C for details.

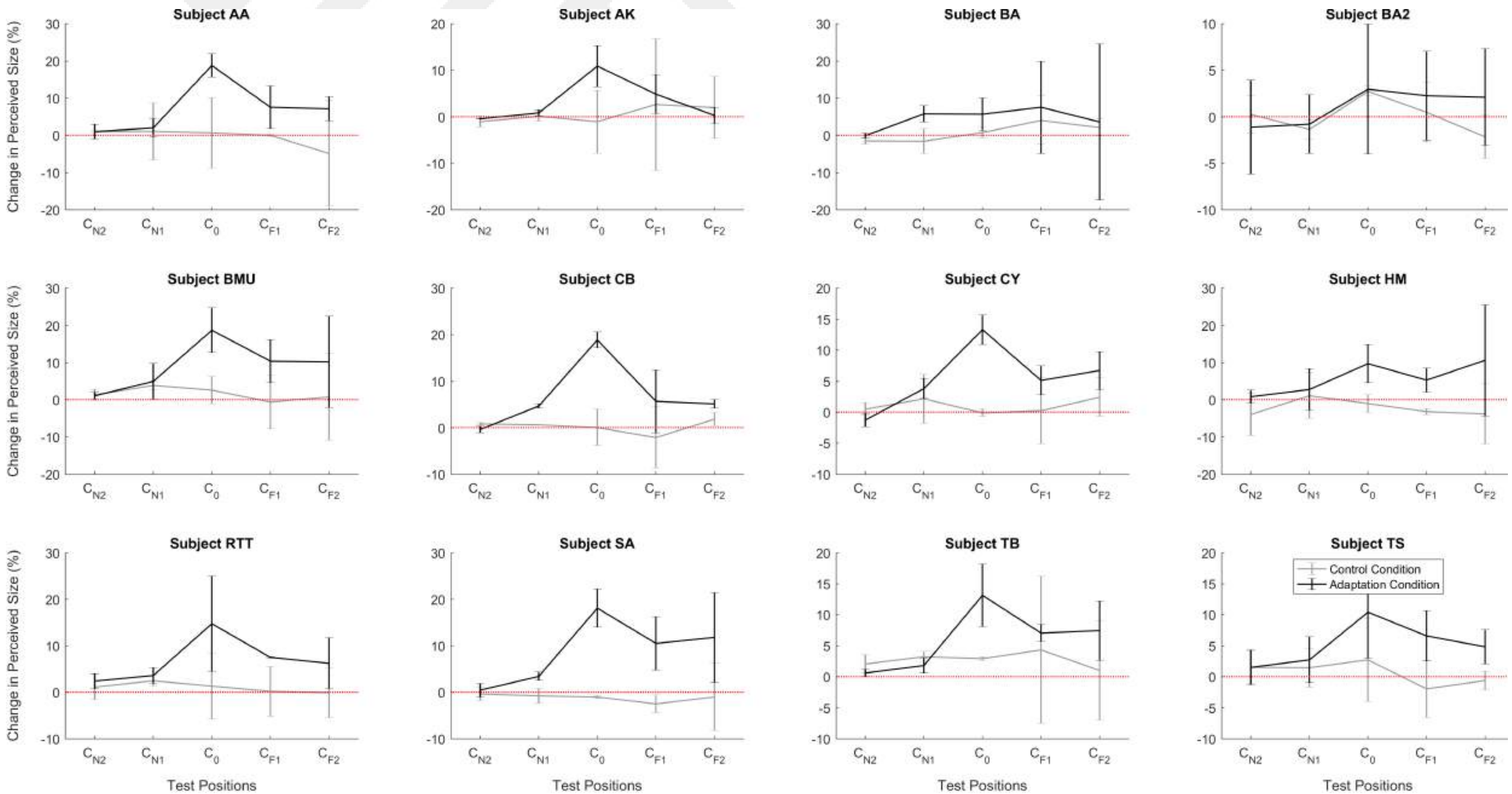

Figure C.10: Large reference disc results of Experiment II-Center positions across subjects. See text in Appendix C for details.

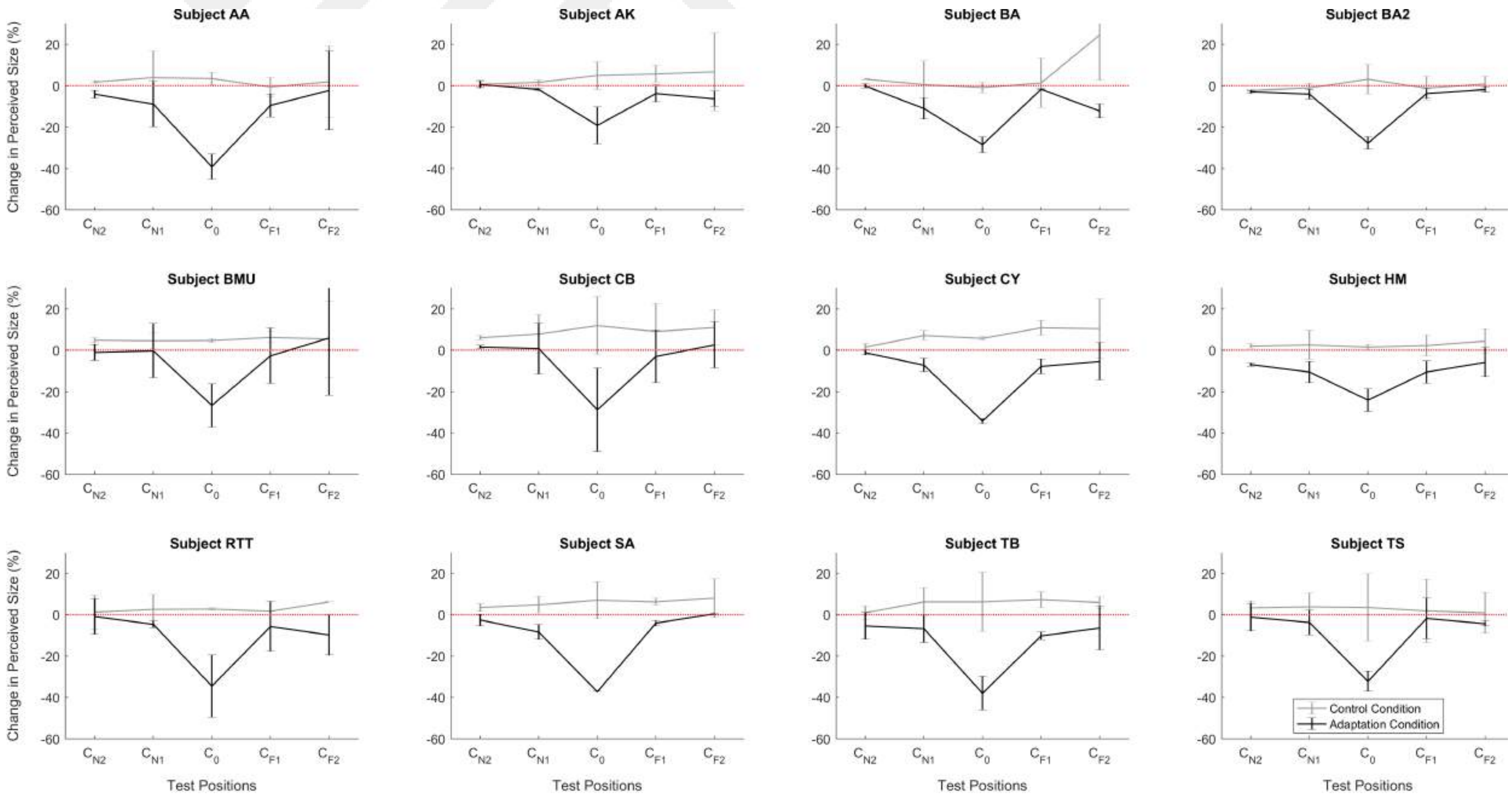

Figure C.11: Small reference disc results of Experiment II-Down positions across subjects. See text in Appendix C for details.

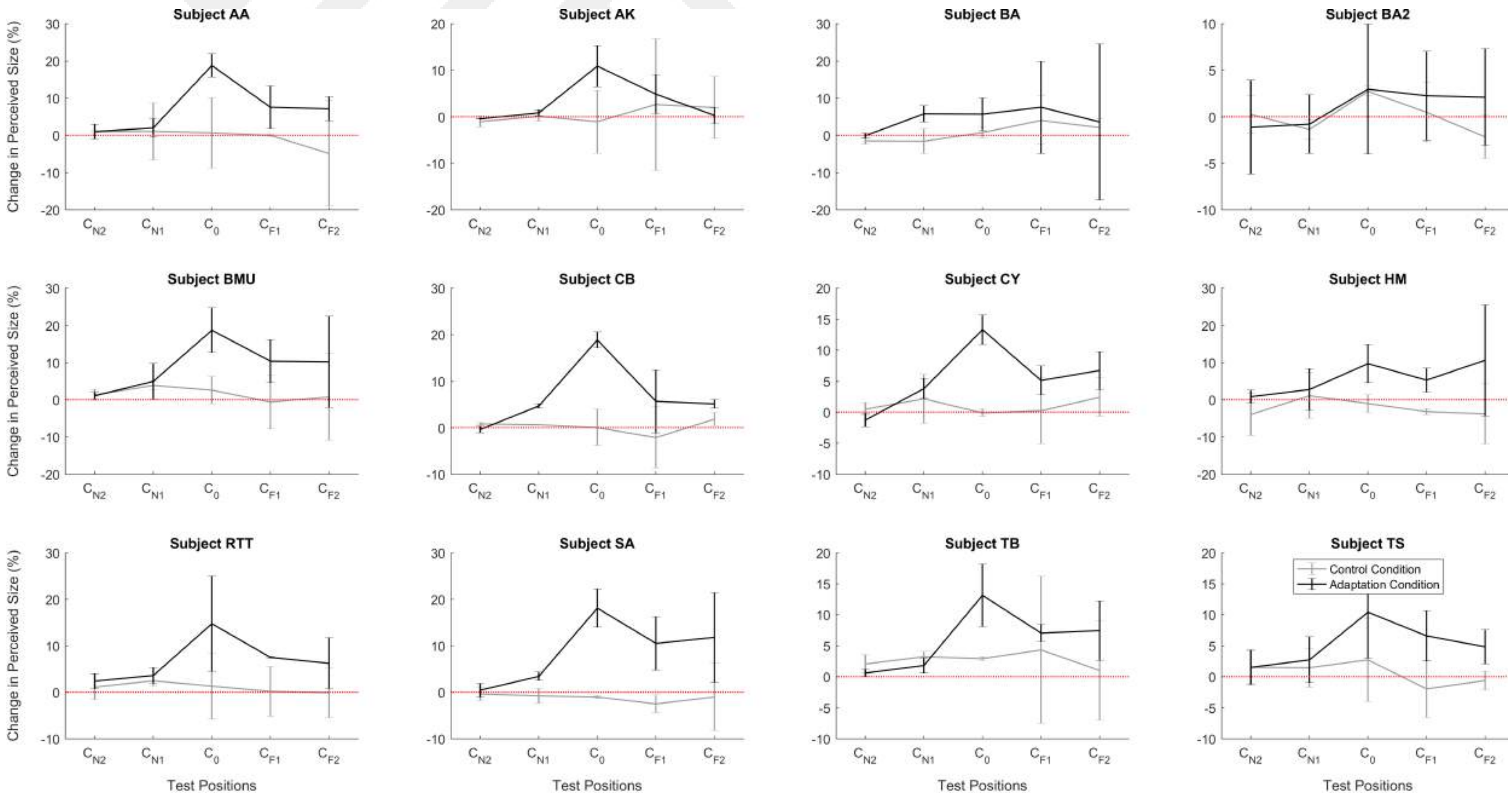

Figure C.12: Large reference disc results of Experiment II-Down positions across subjects. See text in Appendix C for ddetails.

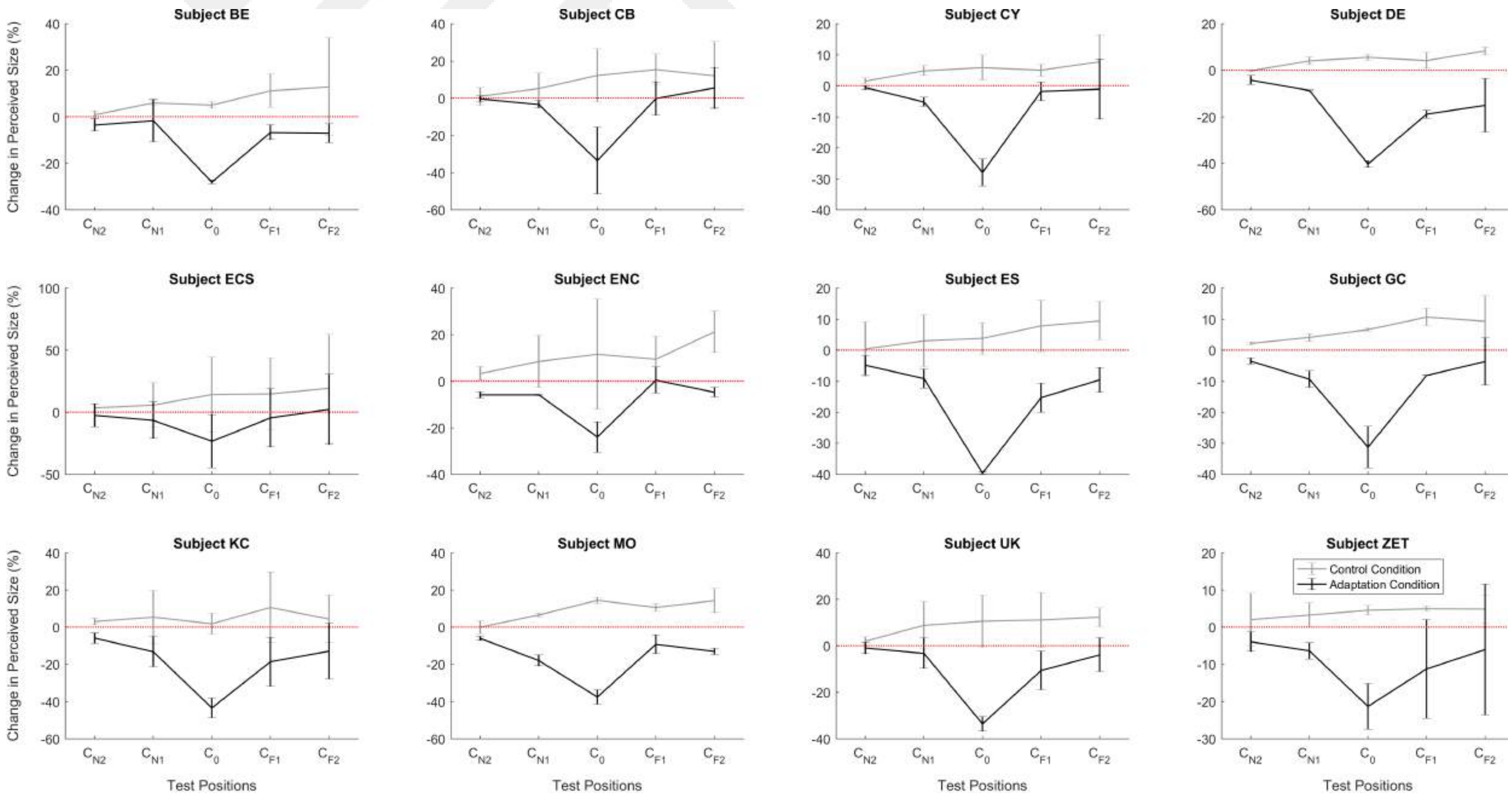

Figure C.13: Small reference ring results of Experiment III across subjects. See text in Appendix C for details.

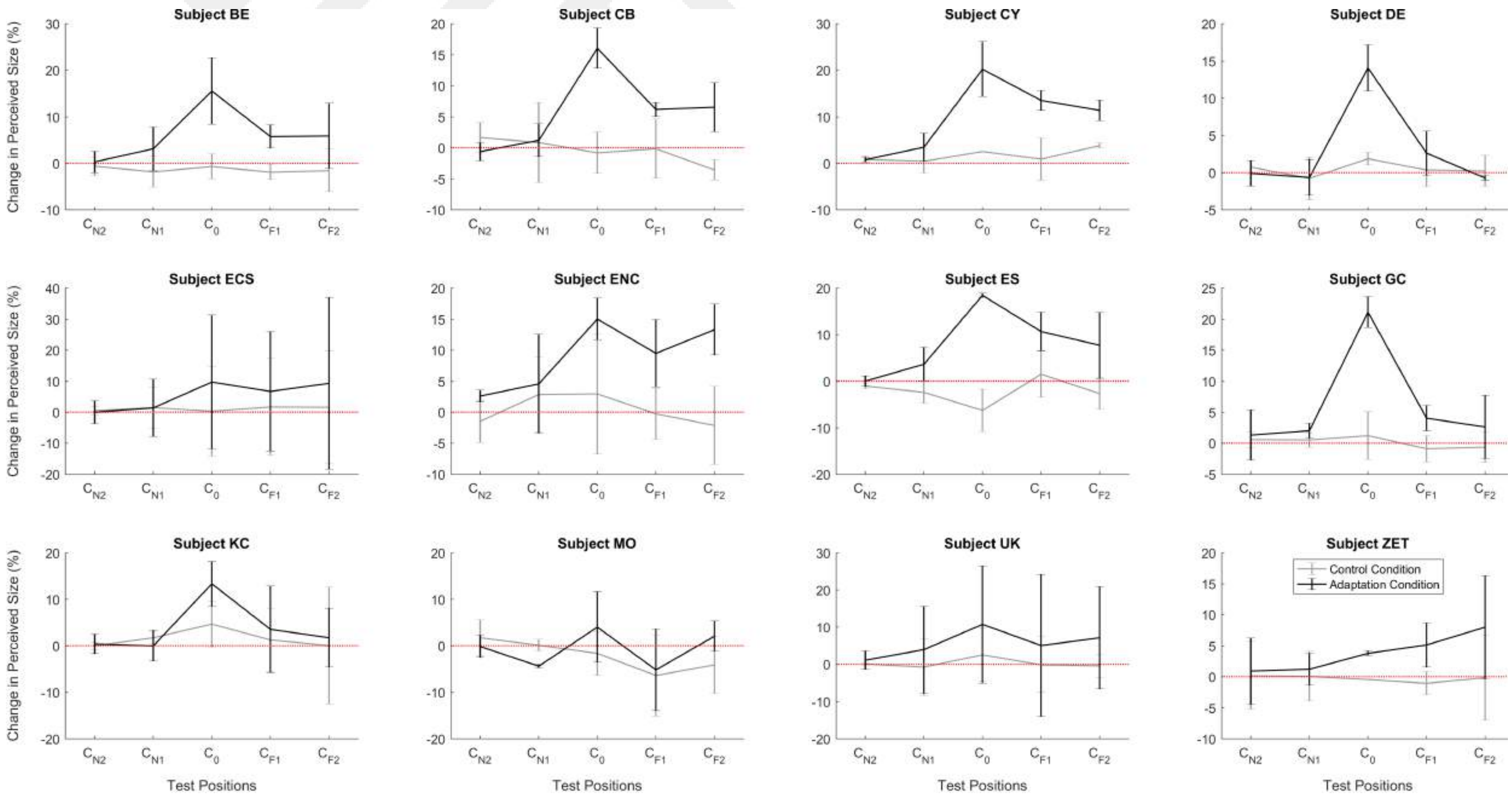

Figure C.14: Large reference ring results of Experiment III across subjects. See text in Appendix C for details.