CATEGORICAL EFFECT STUDIED THROUGH FMRI IN COLOR PERCEPTION

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ABSTRACT

CATEGORICAL EFFECT STUDIED THROUGH FMRI IN COLOR PERCEPTION

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It is widely accepted that color is perceived categorically. Categorical perception (CP) of color can be defined as the tendency to discriminate colors that are from different categories easier, quicker and more accurately than colors that are from the same category. The present study investigated whether brain activity patterns verifies the concept of categorical color perception, an instantiation of top-down influences on low-level perception. Participants performed a color discrimination task on color pairs. Three categories of color pairs are defined in the green-blue region as follows. One of the pairs was specified as cross-category pair by choosing one color from green side of the green-blue boundary and the other color from blue side. The other two pairs were featured as within-category pairs by choosing two shades of green for within-green pair and two shades of blue for within-blue pair. Crucially, the pairs varied only in hue dimension and the physical distance between each of three pairs was set to 10 degrees in CIE LCh space. Pairs on the screen are displayed adjacently or with gaps in between, to further investigate the effect of space in color discrimination. Correct responses, reaction times and fMRI BOLD signals are recorded.

Behavioral findings yielded a decrementing pattern from green to blue region challenging the prediction of categorical perception argument that performance is better at green-blue boundary than both within green and blue regions. Behavioral findings also indicated that adjacent display of colors facilitated color discrimination when compared to display of colors with spatial gaps. Brain activity patterns indicated that separate neural processes might underlie these distinct behavioral differences. Although standardized with respect to the color metric, the three categories of our experiment might have involved differences with respect to difficulty levels and memory requirements. Brain activity differences reported in the within-green condition versus cross-category condition are focused on Frontal Eye Fields and Fusiform Gyrus, which is seem to be modulated by Frontal Eye Field activity; increased activation in these regions is related to enhanced visual performance and higher scores, which is consistent with significantly better performance in within-green discrimination than cross-category discrimination. For the same contrast, Parahippocampal Gyrus and Precuneus activations suggest better visual recall and behavioral improvement due to more efficient maintenance in spatial working memory for within-green discrimination than cross-category discrimination. Brain activity differences reported in the within-blue condition versus cross-category condition is focused on Superior Temporal Gyrus, which is involved in color discrimination having the role of color memory. When within-green and within-blue conditions are compared, there was differential activation in the Fusiform Gyrus, and this is the only brain activity which might be attributed to a categorical effect. This comparison also yielded activity in Medial Frontal and Superior Frontal regions concerning more confident perceptual decisions and improved performance on within-green discrimination than within-blue discrimination. In addition, spatial separation of stimuli entailed more cognitive resources to color discrimination than adjacent stimuli as suggested by Cuneus and Lingual Gyrus activations. Overall, to the best of our knowledge our study is the first to investigate the neural framework for color perception, which revealed that color perception might involve several complex sub-processes that activate memory and attention.

Keywords: event-related fMRI, categorical perception, color discrimination, spatial separation

ÖZ

RENK ALGISI ÜZERİNDEKİ KATEGORİK ETKİNİN FONKSİYONEL MANYETİK REZONANS GÖRÜNTÜLEME YÖNTEMİ İLE İNCELENMESİ

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Rengin kategorik olarak algılanması fikri yaygınlıkla kabul görmektedir. Rengin kategorik algısı farklı kategorilere ait olan renklerin aynı kategoriye ait renklerden daha kolay daha çabuk ve daha doğru ayırt edilmesi eğilimi olarak tanımlanabilir. Bu çalışmada, beyin aktivitesindeki değişmenin, yüksek düzey süreçlerin alt düzey algı üzerindeki etkisinin bir örneği olan kategorik renk algısı kavramını doğrulayıp doğrulamadığı araştırılmıştır. Katılımcılar renk çiftleri üzerinde renk ayrımı yapmışlardır. Yeşil-mavi bölgesinde üç renk çifti kategorisi şu şekilde tanımlanmıştır: çiftlerden biri, yeşil-mavi sınırının yeşil tarafından bir renk tonu ve mavi tarafından başka bir renk tonu seçilerek oluşturulmuş ve çapraz-kategori olarak nitelendirilmiştir. Diğer iki renk çifti, yeşilin iki tonu seçilerek yeşil-içi ve mavinin iki tonu seçilerek mavi-içi olmak üzere kategori-içi özellik taşımaktadır. Çok önemli bir şekilde, çiftler sadece renk tonu boyutunda değişiklik göstermektedir ve her bir çiftin arasında CIE LCh renk uzayına göre 10 derece fark vardır. Renk ayrımındaki uzaysal etkinin ayrıca araştırılması amacıyla renk çiftleri ekranda bitişik ya da aralarına boşluk koyularak gösterilmiştir. Doğru cevaplar, tepki süreleri ve kan oksijen seviyesi bağımlı fMRG

BOLD sinyali kaydedilmiştir. Davranışsal bulgular yeşil alandan mavi alana doğru azalan ve kategorik renk algısı görüşünün mavi-yeşil sınırında hem mavi hem yeşil alan içindekinden daha iyi performans öngörüsü ile çelişmektedir. Aynı zamanda davranışsal bulgular, renklerin bitişik gösteriminin ayrık gösterime göre renk ayrımını kolaylaştırdığını göstermiştir. Beyin aktivitesi yayılımı bu ayrı davranışsal farkların temelinde ayrı nöral süreçler bulunabileceğini işaret etmiştir. Renk metriğine göre standartlaştırılmış olmalarına rağmen deneyimizdeki üç kategori, zorluk derecesi ve bellek gereksinimleri açısından farklılık göstermiş olabilir. Yeşil-içi ve çapraz kategori durumlarının karşılaştırılmasında rapor edilen beyin aktivitesi farkları Frontal Eye Fields bölgesinde ve bu bölge tarafından tetiklen Fusiform Gyrus bölgesinde odaklanmıştır. Bu alanlardaki aktivasyon artışı yüksek skorlar ve gelişmiş görsel performansla alakalıdır ve bu da yeşil-içi ayrımında çapraz-kategori ayrımından daha iyi performans gösterilmesi ile uyumludur. Aynı karşılaştırma için Parahippocampal Gyrus ve Precuneus bölgelerindeki aktivasyon, yeşil-içi ayrımında görsel olarak çapraz-kategori ayrımından daha iyi anımsama ve uzaysal işler bellekte daha etkili tutulma sonucu davranışsal iyileşmeyi göstermektedir. Mavi-içi ve çapraz kategori durumlarının karşılaştırılmasında rapor edilen beyin aktivitesi farkları, renk hafızası yönüyle renk ayrımına dâhil olan Superior Temporal Gyrus bölgesinde yoğunlaşmıştır. Mavi-içi ve yeşil-içi durumları karşılaştırıldığında Fusiform Gyrus bölgesinde aktivasyon farkı oluştuğu görülmüştür ve bu fark kategorik etkiye atfedilebilecek tek beyin aktivitesidir. Bu karşılaştırma ek olarak Medial Frontal ve Superior Frontal bölgelerde aktivasyon farkı yaratmıştır ve bu aktivasyon yeşil-içi ayrımında mavi-içi ayrımından daha emin algısal kararlar verilmesiyle ve artan performansla alakalıdır. Ek olarak, Cuneus ve Lingual Gyrus aktivasyonları, uyaranların ayrık gösteriminin renk ayrımı için bitişik gösterimden daha fazla bilişsel kaynak gerektirdiğine işaret etmektedir. Sonuç olarak, bildiğimiz kadarıyla, çalışmamız renk algısının nöral kapsamını inceleyen çalışmalar içerisinde renk algısının bellek ve dikkati harekete geçiren birçok karmaşık alt süreçler içerebileceğini ortaya çıkaran ilk çalışmadır.

Anahtar Kelimeler: olaya ilişkin fMRG, kategorik algı, renk ayrımı, uzaysal ayırma

To my perfect fiancé

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LIST OF ABBREVIATIONS AND ACRONYMS

3D : Three Dimensional
ANOVA : Analysis of Variance
BOLD : Blood-Oxygen-Level-Dependent
CIE : Committee International d’E’clairage
CCP : Categorical Color Perception
CP : Categorical Perception
cs : cluster size
ERP : Event-related Potentials
FEF : Frontal Eye Field
fMRI : Functional Magnetic Resonance Imaging
ISI : Inter-Stimulus-Interval
IT : Inferior Temporal Cortex
JND : Just Noticeable Difference
LGN : Lateral Geniculate Nucleus
LRH : Linguistic Relativity Hypothesis
LVF : Left Visual Field
N1 : A large, negative ERP component peaking between 80 and 120 milliseconds after stimulus onset
N2 : A negative ERP wave that peaks 200-350 milliseconds after stimulus onset
nm : nanometer
P1 : The first positive-wave ERP component peaking in around 100 milliseconds
P2 : A positive electrical potential peaking between 150 and 275 milliseconds after stimulus onset
P3 : A positive ERP component peaking between 250 to 500 milliseconds after stimulus onset

RT : Reaction Time
RVF : Right Visual Field
STS : Superior Temporal Sulcus
TE : Echo Time
TMS : Transcranial Magnetic Stimulation
TR : Repetition Time
UK : United Kingdom
V1 : Primary Visual Cortex
V2 : Prestriate Cortex
V3 : Third Visual Complex
V4 : One of the visual areas in the extrastriate visual cortex
vMMN : Visual Mismatch Negativity

CHAPTER 1

INTRODUCTION

Color is perceived categorically. Categorical perception (CP) of color can be defined as the tendency to discriminate colors that are from different categories easier, quicker and more accurately than colors that are from the same category (Harnad, 1987). The best illustration of categorical perception of color is the way people perceive the rainbow, which consists of the wavelengths ranging from 350nm to 750nm and incorporates the continuum of visible color spectrum. When we look at the rainbow, we see a number of “bands” of colors and sudden jumps between each two bands of colors, i.e. category boundaries, but not a smoothly changing continuum (Özgen, 2004). The color spectrum is also linguistically divided into categories; different cultures divide the spectrum into different number of categories and name these categories using different color terms (Berlin & Kay, 1969 cited in Roberson & Hanley, 2007).

Categorical color perception (CCP) is described as the significantly increased performance on discriminating between colors which are from different linguistic categories (between-category) and significantly decreased performance on discriminating between colors which are from the same linguistic category (within-category). The category boundaries, namely within- and between-category colors, are determined relying on one of the metrics describing the colors on the continuum.

The tendency to discriminate between-category stimuli better than within-category stimuli is attributed to either innate characteristics (Jameson, 2005) or learning processes influenced by language (Roberson, Davidoff, Davies, & Shapiro, 2005). These two contradictory attributions form the basis for two fundamental and conflicting viewpoints in the research of CCP. Recent evidence suggested that people do the tasks in experiments, such as grouping colors, relying on both their linguistic knowledge and sensory experiences (Claidière, Jraissati, & Chevallier, 2008).

Conducting experiments on the idea that whether people have the same categories of color in perception as they have in language was shown to be the optimal method to test the hypothesis. For some languages linguistic categories used to refer to the same range of color spectrum differ in number. To illustrate, for some African languages, such as Ndonga, linguistic categories are totally different from English. While English has 11 basic color terms to refer to the color spectrum, Ndonga has only six terms to define the whole spectrum. Linguistic category boundaries also do not match between these two languages. For instance, the color range that English speakers call orange is distributed to two linguistic categories in Ndonga: *oshitiligane* (red in English) and *oshishunga* (yellow in English). Similarly, the range that English speakers call pink is included in *oshitiligane* (red in English), and Ndonga language does not include a green-blue boundary. When the speakers of these two languages were asked to choose the most different of three colors, which is called as the triads task, participants reacted according to their linguistic color categories: e.g. when there are two red and one pink on the disk, English speakers tended to choose the pink one, but Africans were equally likely to choose both colors (Pilling & Davies, 2004).

The effect of language on CCP is apparent, however the main argument concerning categorical color perception is that whether CCP is based on the formation of perceptual system or it is resulting from higher cognitive processes during the experience of perception. There is psychophysical evidence revealing that the influence of language appears to be involved in the formation of perceptual system at lower levels rather than intervening at the time of perceptual experience (Notman, Sowden, & Özgen, 2005).

A very critical point in CCP studies is that the researchers analyze their results by dividing performance scores into two groups (between-category and within-category), thus combining the performance scores for within-blue and within-green pairs (e.g. Roberson, Davies, & Davidoff, 2000; Özgen & Davies, 2002; Bimler, 2005; Roberson et al., 2005; Franklin, Clifford, Williamson, & Davies, 2005a; Franklin, Pilling, & Davies, 2005b; Gilbert, Regier, Kay, & Ivry, 2006; Franklin, Sowden, Burley, Notman, & Alder, 2008; Roberson, Pak, & Hanley, 2008; Franklin, Wright, & Davies, 2009; Holmes, Franklin, Clifford, & Davies, 2009; Roberson, Hanley, & Pak, 2009; Siok et al., 2009; Athanasopoulos, Dering, Wiggett, Kuipers, Thierry, 2010; Clifford, Holmes, Davies, & Franklin, 2010; Liu et al., 2010). However, our previous behavioral studies (Koç, 2010) revealed that when the performance on within-blue and within-green pairs is separated, the typical category effect disappears.

Depending on these findings, in order to evaluate the categorical effect on color perception more effectively, performance within the green range and within the blue range is separated and then both are compared with performance on the green-blue boundary. The claim that categorical perception of color is space-dependent rather than being related to verbalization of colors was supported in our previous behavioral studies (Çelik, 2010; Koç, 2010). Therefore, a color metric, which was demonstrated to be perceptually more uniform than others, is needed while defining three conditions:

- **Within-green condition:** Color pairs are within the green range of the color spectrum (two shades of green are discriminated)
- **Within-blue condition:** Color pairs are within the blue range of the color spectrum (two shades of blue are discriminated)
- **Cross-category condition:** One color is taken from the blue side of the blue-green boundary and the other color is taken from the green side (one shade of green and one shade of blue are discriminated)

Importantly, the physical distance, expressed by hue dimension, between each pair should be equated. With these conditions, our previous behavioral data suggested patterns other than categorical perception of color for boundary-green difference and boundary-blue difference. Despite this behavioral evidence, the neural mechanisms underlying these patterns are unknown.

The main aim of the present study is to explore whether there is a change in the activation of any brain areas in response to discrimination of the three color pairs each representing a different categorical relationship, rather than reflecting just between-category and within-category difference.

The present fMRI experiment is designed considering the impact of both color space used to assign color pairs and separation of within-category colors on the results. Relying on our previous behavioral studies, performance is expected to decline on the blue region. Therefore, the neural mechanisms underlying the difference between cross-category and within-blue conditions should be different from those underlying the difference between cross-category and within-green conditions. The secondary purpose of the present study is to examine whether there is a neural effect of spatial separation of color pairs. Therefore, the spatial display, on which color pairs are discriminated, is also manipulated:

- **Adjacent condition:** Color pairs are displayed contiguously as a rectangle
- **Separated condition:** Color pairs are displayed having a gap between them as four squares

Considering the display organization, it is predicted that adjacent presentations yield better performance than spatially separated presentations.

Following this introductory chapter, a detailed background on categorical color perception will be given in Chapter 2. Literature will be surveyed under five parts: first part will summarize the theoretical arguments behind the topic, second part will explain the neural correlates of color perception, third part will focus on categorical effects on this perceptual process, forth part will clarify the metrics in which color is defined, and fifth part will emphasize spatial organization of the display area in which colors were presented. Finally, hypotheses concerning our study will be listed at the end of Chapter 2.

Chapter 3 will describe the methodology, design, data acquisition and analysis process. Chapter 4 will provide the results of the present experiment and Chapter 5 will discuss the results. Chapter 5 will state the conclusions for the current work and suggest future work.

CHAPTER 2

BACKGROUND

There is an ongoing debate about whether categorical perception of color occurs naturally or it is the result of verbal labeling. There are two main perspectives on the origin of categorical effects observed in color perception: Universalism maintains that this effect is innate and Linguistic Relativism proposes that this effect is learned.

2.1 Universalists versus Linguistic Relativists

According to **the Universalist view**, which supports the idea of innateness of CP, color categorization is genetically determined (Jameson, 2005). The resemblance between cultures in color naming is explained by shared neurological pathways dedicated to color discrimination in the brain (Bimler, 2005). Early cross-cultural evidence suggested that participants have learning and memory capacity for basic colors even if they did not have the categories in their language (Rosch Heider, 1972). Studies of the perceptual process of CCP in infants revealed results supporting the Universalist view. In a habituation experiment, it was found that infants as young as four-months showed CCP and could divide the color spectrum into four basic categories -red, green, blue, and yellow- (Bornstein, Kessen, & Weiskopf, 1976). In a more recent study using ERP, neurological evidence was found showing CP of color in seven-month-old infants (Clifford, Franklin, Davies, & Holmes, 2009). In a behavioral study, English and Himba toddlers were tested and it was found that despite lack of a linguistic boundary in Himba language for the tested region of the color spectrum, CCP exists in toddlers irrespective of culture and the extent to which toddlers acquire color terms does not influence the strength of the categorical effect (Franklin et al., 2005a). In another behavioral study recording eye movements, CCP in four-month-old toddlers was compared to that of adults and results indicated that both groups responded faster to targets when they were presented on a background such that the target and the background form a between-category relationship than when the target and the background are from the same category (Franklin et al., 2005b). A more recent study relying on behavioral data suggests that toddlers show CCP on a given category boundary even when they do not know the color terms to refer the tested colors, and moreover, even if their language does not include a category boundary for the tested region of color spectrum (blue-green area) (Franklin et al., 2009). These findings suggest a genetic component in acquisition of CCP, which seem not to be affected by linguistic characteristics.

On the other hand, according to the idea called **Linguistic Relativity Hypothesis (LRH)**, culture, more specifically language, affects how people's minds work (Lucy, 1997). It was argued in a review of studies concerning color terms used in different cultures that the large scale of variability across cultures in naming the colors is against the universality of dividing and perceiving the color spectrum (Roberson & Hanley, 2007). In the course of time human brain does task distribution based on what was learned. It is inevitable that culture has a major role on what was learned. Some cultures divide the color spectrum in a way that is different from other cultures; they do not have some of the category boundaries (e.g. for blue-green discrimination) in their language and this lack of category boundary in their language was also evident in their perception which was revealed in visual search and visual oddball tasks (Özgen, 2004). Similarly, when English and Turkish students were told to group colors according to similarity, results indicated that English students grouped blue and darker blue into one category, because they have no category boundary for these colors in their language (they use just "blue" for both). On the other hand, Turkish students grouped these colors into two different categories; their language has a category boundary for the two blue colors (i.e. mavi and lacivert) (Özgen, 2004). LRH can also be tested by perceptual learning, in which CCP can be induced by repeated exposure to a novel category boundary (Özgen & Davies, 2002). If language learning shapes mental representations, then learning new color categories results in CCP on that category boundary (Pilling & Davies, 2004). Evidence suggested that people could acquire CCP by learning a new category boundary through laboratory practice (Özgen, 2004). Performance is improved on the practiced characteristics of stimuli and the idea of perceptual learning is tightly related to plasticity of the brain. The term plasticity refers to the ability of underlying neural mechanisms to improve or change its processing as a result of repeated exposure: people become more sensitive to practiced characteristic of given stimuli (Polat, 2009).

2.2 Color Processing in the Brain

Color information coming from three different types of cone cells (S, L, and M cones) first projects to the lateral geniculate nucleus (LGN), which contains two clusters of cells responsive to two different combinations of cone signals (Komatsu, 1998). Then this information is transmitted to the primary visual cortex (V1), where the neurons are much more color-selective and constitute groups responding to different hues overlapping by different proportions according to the similarity of hues they represent (Xiao, Casti, Xiao, & Kaplan, 2007). Similarly, higher visual areas in the occipital lobe such as V2 (Ts'o, Roe, & Gilbert, 2001) and V4 (Conway, Moeller, & Tsao, 2007) include neuron populations, each tuned to a different range in the color spectrum and located on the cortex accordingly (Xiao, Wang, & Felleman, 2003). While assessing the mechanisms of human brain, addressing macaque brain due to advantage of neuron-based measurements is a preferred way since there is considerable resemblance between functioning of their visual systems (Komatsu, Ideura, Kaji, & Yamane, 1992). Employing single cell recordings, it is found that color information proceeds to ventral pathway, i.e. the "what" pathway, through inferior temporal cortex (IT), which is known to be the site for object recognition (see Figure 2.1). The neurons in IT are also color-responsive in a modular manner (Komatsu et al., 1992), being spatially organized with respect to the hues of tuned colors (Conway & Tsao, 2009).

A number of structures in the human brain were identified as color-processing regions such as V4 (Bartels & Zeki, 2000), fusiform gyrus (McKeefry, & Zeki, 1997), and lingual gyrus (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991). Gonzalez, Relova, Prieto, Peletiero, and Romeo (2006) evaluated electrical signals elicited by

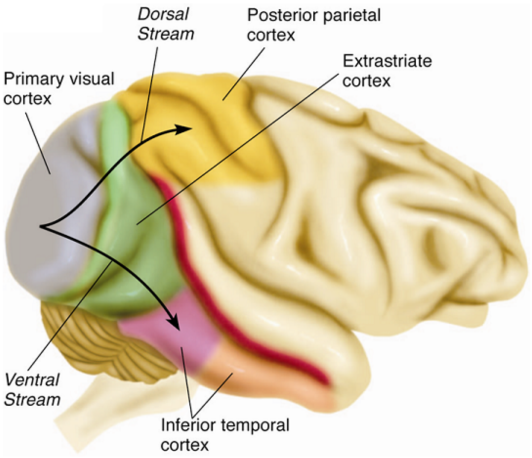


Figure 2.1: Dorsal ("Where") and Ventral ("What") Cortical Visual Pathways (Chapter 2 in Smith & Kosslyn, 2006)

electrodes placed in the fusiform gyrus of a patient with occipital epilepsy. While she was looking at a fixation cross, a square area among the random grey dots on the background abruptly switched to colored dots. The results indicated that when the dots turned to colored square area on the contralateral side, the electrical signal got stronger and when it was on the ipsilateral side, fusiform response significantly decreased: the fusiform activity was dependent on the visual hemifield of the color stimulation. The authors concluded that this area may not be the terminal site in color processing and it seemed that further operations were required to integrate color information from both hemifields.

2.3 The Influence of Color Categories

The argument that color processing in the brain is categorical is generally based on the results pointing hemispheric asymmetries during color perception (Drivonikou et al., 2007). The influence of language in the formation or operation of brain areas dedicated to color processing has been investigated in a number of studies which looked at the relationship between language and color vision. For instance, in an fMRI study, categorical perception of color, which is characterized by stronger and faster brain activation in response to between-category color pairs than within-category color pairs, was found to be more intense when stimuli were shown in the right visual field (RVF-left hemisphere) than when they were shown in the left visual field (LVF-right hemisphere) (Siok et al., 2009). Additionally, and more importantly, when the color pairs were shown in RVF, the activation in visual areas is accompanied by activation in left posterior temporoparietal language region. This additional activation could be the indicator of a top-down processing modulating color perception.

Categorical color perception was investigated in ERP studies more than fMRI studies. For instance, relationship between language and color perception was found in a study that investigated the lateralization of CCP in infants and in adults using ERP (Franklin et al., 2008). The typical categorical effect was found in left hemisphere in adults and in infants who had already acquired color terms and in right hemisphere in infants who had been learning the terms. In a more recent ERP study employing an oddball task, the delay between stimulus presentation and the response it triggers was found to be shorter in between-category trials than within-category trials for P1 and N1 components, in addition to the stronger signals in response to between-category stimuli measured by P2 and P3 components (Holmes et al., 2009). The former components indicate a perceptual effect, whereas the latter components point a top-down modulation of attention according to stimulus characteristics. In order to dissociate early effects on categorical color perception from the involvement of top-down attentional processes, the signal from vMMN component of ERP was recorded while participants were performing a visual oddball task (Clifford et al., 2010). This component measures automatic and pre-attentive visual discrimination, therefore, stronger records from this component in response to between-category stimuli than within-category stimuli connotes that categorical effect is very early, even before the conscious level, in color perception. In another study (Liu et al., 2010), participants were required to decide whether two features of a stimuli, presented in either hemifield, have the same color. N2 component, signaling the conflict detection in frontal regions, recorded stronger responses to within-category stimuli presented in RVF than to between-category stimuli presented in RVF. The authors infer that the significant signal difference is likely to suggest language effects in left hemisphere caused by within-category stimuli belonging to the same linguistic category so deteriorating the ability to discriminate colors. In a more direct examination of language-related effects on color perception (Athanasopoulos et al., 2010), Greek participants who had been living in UK were tested using a color oddball task. For the given green-blue range of the color spectrum, while English speakers use two terms, Greek speakers use three terms dividing the blue region into two as lighter blue (ghalazio) and darker blue (ble). Consistent with the linguistic relativism, the vMMN component recorded stronger signals in response to blue stimulation than to green stimulation for the Greek speakers who stayed in UK for a short period. On the other hand, for the Greek speakers who stayed in UK for a long period, the ERP signals were similar to the English speakers. This study shows the influence of linguistic environment on early perception.

2.4 Space Dependency of Categorical Color Perception

The most challenging aspect of categorical color perception (CCP) is that faster and more accurate discrimination of colors that are from different categories than colors from the same category occurs despite the fact that the "distances" separating the color pairs are equal. This aspect leads to the operationalization of the research question (see Figure 2.2). For example, the blue-green region of the color spectrum is divided equally, i.e. the physical distance between colors is equal (shown by d in Figure 2.2), but the perceived distance (Pd in Figure 2.2) between the color pairs which cross the category boundary (dashed line) is greater than the perceived distance between color pairs which belong to the same linguistic category (Özgen, 2004). In other words, people tend to discriminate between B2 and G2 easier than between B1 and B2 or between G1 and G2.

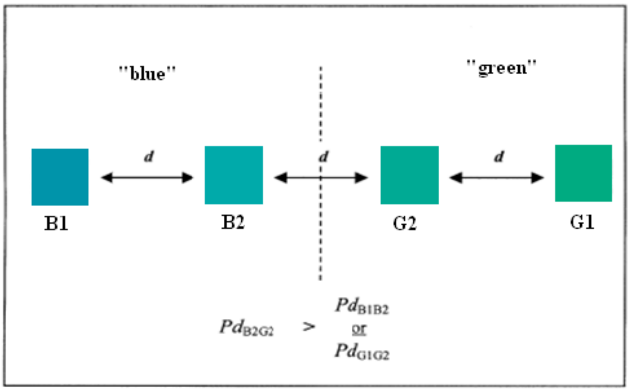


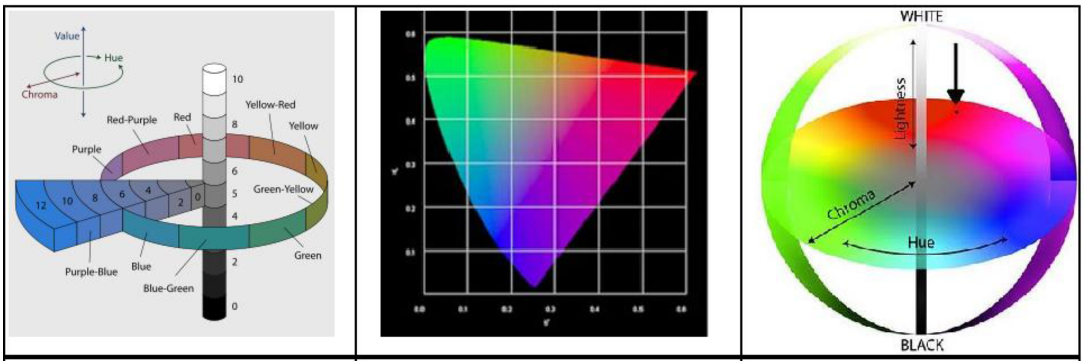
Figure 2.2: Operationalization of CCP (Özgen, 2004)

Assigning the units which describe the stimuli within a given continuum, or more specifically, dividing the visible spectrum with equal distances, so determining the category boundaries and focal points along the color range is very critical in studying CCP. Different parameters are used while designing the experiments. For instance, Bornstein and his colleagues (1976) divided the blue-green region by 30-nanometer (nm) increments; they used wavelength as the color metric.

The color spectrum is divided using metrics that are assumed to be perceptually uniform, where the most widely used and respected space in the research of categorical color perception is Munsell color metric, which defines the color spectrum according to three independent characteristics (see Figure 2.3): hue (five primary hues and five intermediate hues), value (lightness dimension, between 0 and 10) and chroma (saturation of colors, ranging between 0 and 12 with two-step increments). The classic pattern of categorical color perception was evident in several experiments that described color stimuli in Munsell space (e.g. Roberson, et al., 2000; Özgen & Davies, 2002; Bimler, 2005; Roberson et al., 2005; Franklin et al., 2005a; Franklin et al., 2008; Roberson et al., 2008; Franklin et al., 2009; Holmes et al., 2009; Athanasopoulos et al., 2010; Clifford et al., 2010; Liu et al., 2010). Albert Munsell constituted his metric experimentally by asking participants arrange colors on a color tree; therefore, the Munsell metric reflects how people characterize colors (Landa & Fairchild, 2005). Because this space relies totally on human perception, instead of mathematical calculations to create symmetrical grids on a continuum, it contains discrete and irregular definition of colors.

Some researchers supplement CIE (Committee International d'E´ clairage) L*u*v* color space, where L* is lightness, u* is redness-greenness, and v* is yellowness-blueness of a given color (see Figure 2.3), to the Munsell space (e.g. Franklin et al., 2005b; Goldstein, Davidoff, & Roberson, 2009). Computer and television technology depending on colored lights necessitated definition of this kind of a physical color space (Yeh & Gu, 2009). Three parameters within this metric aimed at creating a linear color space, thereby implying uniformity in perceiving color differences on different dimensions (Ford & Roberts, 1998b).

In addition to Munsell and L*u*v* color spaces, another respected color metric is CIE LCh color space. Colors are defined in a spherical manner in CIE LCh space and L refers to luminance (values ranging between 0-black- and 100-white-), C is chromacity (values ranging between 0-no saturation- and 100-high saturation-) and h is hue angle (0° represents red, 90° represents yellow, 180° represents green and 270° represents blue). This is a color-opponent space representing all visible colors and used for more advanced software.



MUNSELL COLOR SPACE | CIE L*u*v* COLOR SPACE | CIE LCh COLOR SPACE

Figure 2.3: Overview of Color Spaces

In a recent paper, Roberson, Hanley, and Pak (2009) tested two groups of participants; English speakers whose language includes two color terms for a given range of colors (blue and green) and Korean speakers whose language includes three color terms for the same range of colors (chorok, cheongrok and parang). The authors hypothesized that when access to verbal codes for color is prevented, there would be no categorical effects; therefore CCP is the result of linguistic interference rather than being truly perceptual. There were two experiments in the study: the first experiment measured the discrimination thresholds (JND) to identify the smallest difference between two shades of colors detected by the participant, and the second experiment measured same-different judgments of participants. In experiment 1, the stimuli was shown as a rectangle which consists of color pairs, one of the colors in a given pair constitutes one third of the rectangle and appears whether on the right or the left side of the rectangle. The procedure of this experiment was claimed to eliminate the interference of any verbal code of colors. The results of the experiment revealed no significant difference between the two groups at any category boundary for both languages, in other words, the participants did not show reduced thresholds for the category boundaries of their own language. In the second experiment, color pairs were shown as two separate squares and the participants were required to determine whether the two colors are the same or different. Typical CCP effect was found in this experiment; participants discriminated the color pairs better when they are from different categories in their own language than from the same category. The authors attributed these results to the argument that the first experiment includes only the perceptual component-low level of perception- while the second experiment includes an additional linguistic component-higher-level processing-. It is worth to note that there was a crucial difference, in fact a confounding variable, which may lead to the presence or absence of CCP effect, between these two experiments: in the first experiment, which resulted with no categorical effects, the color pairs are defined in CIE L*u*v* color space but in the second experiment, which showed categorical effects, the color pairs are defined in Munsell space. This is a fundamental distinction between the two experiments and further analysis is required in order to demonstrate whether defining the color pairs in different color spaces has an influence on the results. The potential effect of color space on categorical color perception was also discussed in another study. Özgen and Davies (2002) stated that even though they assumed Munsell space as a perceptually uniform metric, they realized perceptual differences within a given category. In other words, the pairs that are closer to category boundary were discriminated better than pairs that are more central in the category. Therefore, they suggested CIE L*u*v* space as an alternative measure of distances between colors. Such discrepancies within the Munsell space was reported even earlier (Indow, 1988).

Recently we investigated (Koç, 2010) whether the categorical effect on color perception is due to linguistic interference or it depends on the color space which was used to determine and describe the stimuli. In order to test the space dependency hypothesis, the participants were assigned to two conditions. In condition-1, color pairs that are derived from blue-green area of color range are presented on the screen in the form of a rectangle (adjacent to each other) and were defined in either Munsell color space, whereas in condition-2, CIE L*u*v* color space is used. It was predicted that the difference between conditions found by Roberson et al. (2009) has nothing to do with the level of perception or verbal interference; instead, it was because of the space dependency of categorical perception of color. For this purpose, adjacent color pairs were defined in both Munsell and CIE L*u*v* spaces. This prediction was also tested in a complementary study (Çelik, 2010) in which the color pairs were presented in the form of two separated squares and were defined in either Munsell color space or CIE L*u*v* color space. It was expected that CP of color would be found for color pairs that were defined in Munsell space and categorical effect would be absent for color pairs that were defined in L*u*v* space.

The results of our experiments revealed implications about perceptual uniformity of widely used color metrics. The prediction that categorical perception of color is space-dependent rather than implying the effect of the level of perception or verbal interference was supported. When the adjacent color pairs were defined within the Munsell color space, the results revealed a typical categorical perception pattern; local minima for points which are likely to consist of within category pairs and local maxima for points which are likely to consist of pairs that cross the category boundaries. However, when these pairs were transformed into CIE L*u*v* space the responses to color pairs within the given interval revealed much more linear results that were not affected by the pairs being whether within-category or between-category. This evidence supports the claim that the results of Roberson, Pak, Hanley (2009) cannot be attributed to having a gap between the pairs during the presentation allowing the observers to use verbal labels during the discrimination of the color pairs. The absence (Koç, 2010) or presence (Çelik, 2010) of gap between the color pairs makes no difference; the space which is used to define the colors determines categorical perception.

The most critical point made by these studies is that they suggest a perceptually uniform space, namely CIE LCh, as evidence of the uniformity established by equal performance throughout the given blue-green region. In fact, the CIE L*u*v* space was nearly uniform, but there were some unsystematic fluctuations in performance throughout the given blue-green region. On the other hand, it is impossible to talk about uniformity when it comes to Munsell color space. This is due to the fact that the Munsell metric relies on human perception of a given stimuli; seemingly it cannot be as reliable as a physically based space. Furthermore, the performance within the Munsell space forms a systematic pattern, which may be caused by a bias of the human visual system.

2.5 The Influence of Spatial Separation of Color Pairs

Danilova and Mollon (2006) examined the effect of presenting a spatial gap between color stimuli. They displayed two pieces of colors on the screen and measured how well participants perceived the difference between them. Performance in discriminating two pieces of colors was highest when the color pair was separated using a particular size of gap between them, not when the pairs were contiguously presented (left screenshot in Figure 2.4). Performance was found to decrease gradually as the particular size of gap was exceeded; for instance right screenshot in Figure 2.4 shows the maximum gap where performance was the worst. The most crucial methodological detail in this experiment was that the color pairs were displayed within a hypothetical circle so that the center of each pair was positioned on the circle. The radius of this hypothetical circle was 5° of visual angle and both the distance between centers of simultaneously presented pairs and the distance between their closest borders was calculated in terms of visual angle. The adjacent example shown in Figure 2.4 represents 2° of separation between centers of the two color patches and the separated example shown in the represents 10° of separation between centers of the two color patches. Results of the color discrimination task revealed that when the performance scores reached the peak value, there was 1°-2° of separation between their nearest borders which corresponds to 3°-4° of separation between their centers.

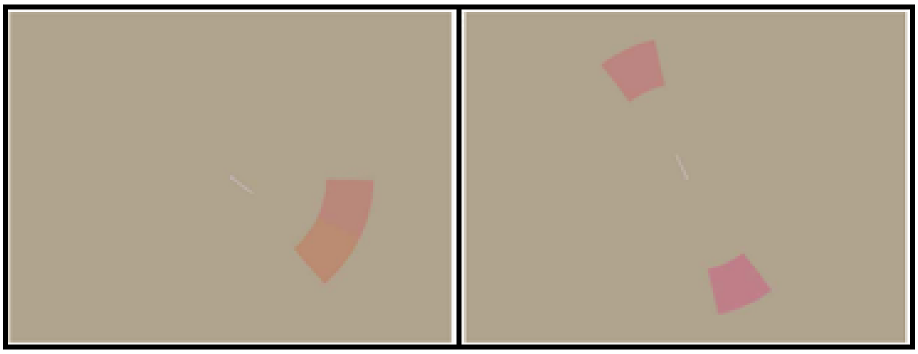


Figure 2.4: Sample stimuli from Danilova and Mollon (2006)

2.6 Hypotheses in the Present Study

Two general questions are investigated in the present study:

- How is discrimination of colors that belong to different linguistic categories realized in the brain?
- How is discrimination of colors that have different display properties realized in the brain?

These research questions will be investigated by defining three category-related conditions (within-green, cross-category, and within-blue) and two display-related conditions (adjacent and separated). The hypotheses in the present study can be listed as follows:

- H1: Performance on blue color discrimination was found to be worse than green and cross-category discriminations in our previous studies. Therefore, performance should yield a decrementing pattern towards the blue region in terms of both accuracy and reaction time.
- H2: Considering behavioral effects found previously, activation contrast for within-blue and cross-category conditions should be in a form that is different from within-green and cross-category contrast.
- H3: If verbal codes interfere with categorical perception of color, as Linguistic Relativism suggests, then language areas in the brain should be differentially activated in cross-category condition than both within-blue and within-green conditions.
- H4: Spatial proximity of colors is considered to make their discrimination easier. Therefore, performance should be better when color pairs are displayed adjacently than when they are separately displayed.
- H5: The perceptual advantage in adjacent display should also be seen in brain activation patterns.

CHAPTER 3

METHOD

The methodological details of the present experiment, including subject demographics, materials, procedure, design and analysis are explained in the following parts.

3.1 Participants

There were 20 participants: 10 females and 10 males. The mean age was 23 years (±1,57). They were mostly Bilkent University undergraduates. All of the participants had normal color vision as tested by the Ishihara Color Blindness Test (Appendix A). They all read and signed informed consent form (Appendix B). Ethical approval was granted by Ankara University Medical Faculty Clinical Research Ethics Committee (Appendix C).

3.2 Stimuli

Stimuli were three color pairs (within-green pair, cross-category pair and within-blue pair) defined in CIE LCh color space. Initially, the midpoints were determined varying in the hue angle (h=160° for green; h=187° for category boundary; h=220° for blue). Lightness and chroma were kept constant at 57 and at 0.57 respectively. The three color pairs were assigned setting five units below and above each midpoint; therefore, the distance between the two colors of each pair is set to 10 units. The manipulation of the color pairs and representational demonstration of midpoints and both colors of each pair can be seen schematically in Figure 3.1. For instruction, a demonstration trial including one pair of grey stimuli was used. Practice trials included five grey pairs with five difficulty levels.

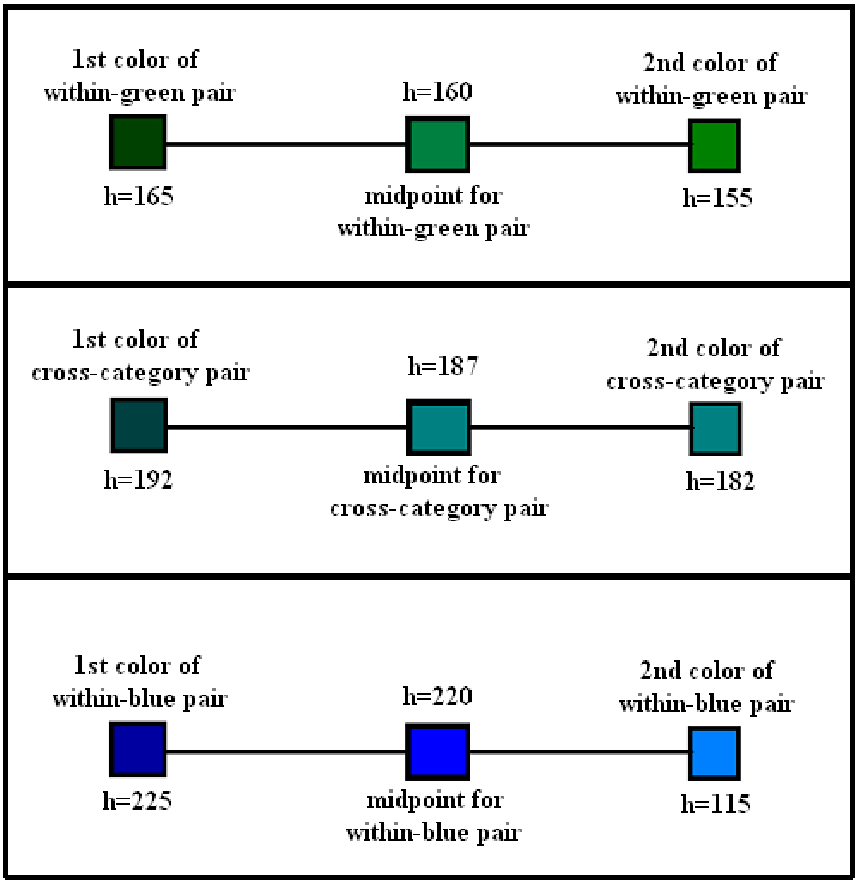


Figure 3.1: Schematic illustration of the manipulation of three color pairs. Midpoints and both colors of each pair are represented.

The colors within the same pairs were displayed adjacent to each other with a six-pixel Gaussian blurred edge between them in a 20x5 cm rectangle, the rightmost or the leftmost quarter of which was formed by one color of a given pair and the remaining region was formed by the other color of the same pair in one condition. In the other condition, the colors within a pair were spatially separated as four 5x5 cm squares next to each other with a 2cm space between them, the rightmost or the leftmost square is formed by one color of a pair and the remaining squares on the same screen are formed by the other color of the same pair. The visual angle subtended by the stimuli was 3 degrees. The two presentation alternatives of the color pairs in terms of spatial display are schematically demonstrated using within-green and within-blue pair simulations in Figure 3.2; within-green representation illustrates rectangle/adjacent condition and within-blue pair illustrates square/separated condition. The stimuli were displayed on a neutral grey background, which was described as (0.3101, 0.3161, 50) in CIE x,y,Y units.

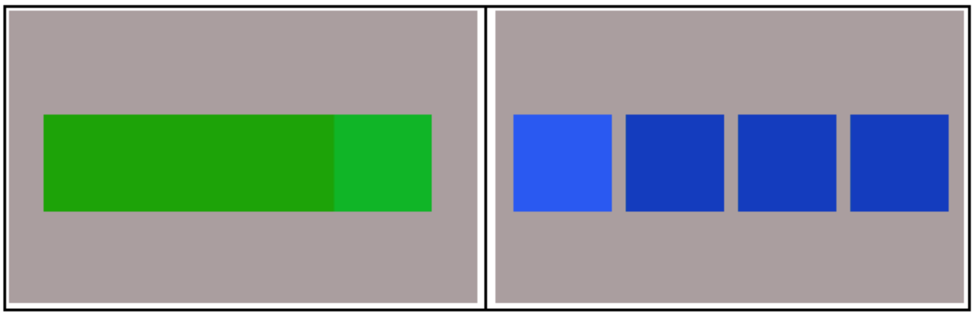


Figure 3.2: Schematic demonstration of the two presentation alternatives in terms of spatial display using simulations of within-green pair and within-blue pair. Rectangle/adjacent condition is on the left (within-green simulation). Square/separated condition is on the right (within-blue simulation).

Two-alternative-forced-choice task was used. If the “different” color is on the right side of the screen, the subject was asked to press the button on the right of the response box and if the “different” color is on the left side of the screen, the subject was asked to press the button on the left of the response box. Correct choices were counterbalanced. For example, for the within-green pair representation shown on the left screen in Figure 3.2, the participants are expected to press the right button, but for the stimulus pair given on the right screen in the figure, which shows a within-blue pair representation, the participants are expected to press the left button.

3.3 Apparatus

A personal laptop (Casper Nirvana NB 15.6 CPQ 1350 3K35B) running the computer program designed for the experiment was used. The stimuli were reflected in the scanner by a projector (NEC NP 1250) fitted with a long throw lens (NuView zoom lens 489MCZ900, Navitar). The color pairs were back projected onto a translucent back projection screen placed inside the scanner bore with the help of an angled first surface mirror (Da Lite). Observers viewed the stimuli formed on the translucent screen through another angled first surface mirror located above their eyes and fitted to the head-coil by a custom made apparatus (Aref Medikal). Projector calibration was made using a high performance spectroradiometer, SpectroCAL (Cambridge Research Systems).

3.4 Procedure

The first thing in the experiment was to assess participants' color vision in daylight using the short version of Ishihara Color Blindness Test. After the assessment, participants were instructed showing a demonstration trial. The stimuli were displayed by the experimenter pressing the space bar; the display was the same as the real trials. The observers were told that the trials would be the same as the demonstration, but it would run spontaneously and rapidly.

After being positioned in the scanner, the first thing the observers did was to practice the experiment. The course of practice trails was the same as the real experiment, but there were ten trials including only the shades of grey color with five difficulty levels. The color pairs were presented in the order of their difficulty levels. Responding 10 subsequent practice trials correctly was essential to passing this stage. If the observer responds incorrectly, s/he had to turn back to the beginning of the practice. After the participants succeeded the practice trials, fMRI experiments were started. The subjects were debriefed regarding the experiment when the scanning session ended.

3.5 fMRI experiment design

The experiment was an event-related fMRI design, administered through three runs. A 3x2 experimental design was employed: color category with three levels (within-green, cross-category, and within-blue) and spatial display with two levels (adjacent and separated). Hence, there were six experimental conditions in total. Each of these six conditions was presented in 12 trials in each run. Therefore, each run was composed of 72 trials and took about five minutes. The possible presentations of a given color category can be seen in Table 3.1.

There were 216 trials separated by the three runs with 72 trials for each run. The sequence was the same for each run. First, the fixation cross appeared and stayed on the screen for 20 seconds. Then, the trials started. Each stimulus stayed on the screen for 500ms. For each trial, the colors forming either the left or the right part of the display was different from the other parts. The order of the stimulus presentations

Table 3.1: Possible Presentations of a Given Color Category

COLOR PAIR	SPATIAL DISPLAY	POSITION OF THE "DIFFERENT" PAIR
Pair 1 of the category	Adjacent	Right
Pair 1 of the category	Adjacent	Left
Pair 1 of the category	Separated	Right
Pair 1 of the category	Separated	Left
Pair 2 of the category	Adjacent	Right
Pair 2 of the category	Adjacent	Left
Pair 2 of the category	Separated	Right
Pair 2 of the category	Separated	Left

was random for each run and for each subject. Each stimulus is followed by an Inter Stimulus Interval (ISI) randomly alternating between 1500ms 3500ms and 5500ms. The ISIs were ordered using m-sequences function in MATLAB. A fixation cross against the gray background stayed on the screen during the ISI and the participants were required to respond during the ISI. Lastly, the fixation cross stayed on the screen for 10 seconds at the end of the runs. An example fMRI task waveform is provided below in Figure 3.3.

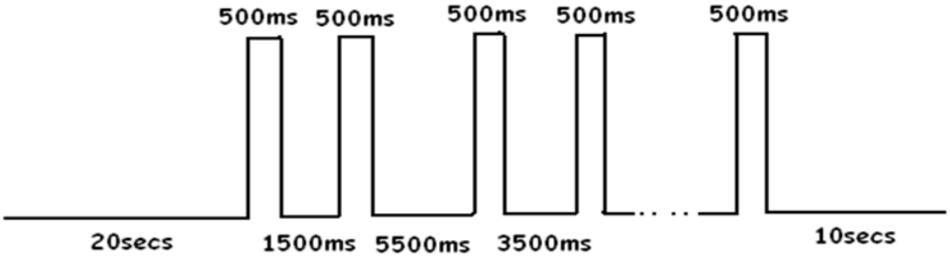


Figure 3.3: Example fMRI task waveform

3.6 Data Collection

Data was collected on a 3T Siemens Trio scanner positioned in the UMRAM center at Bilkent University. Initially, a four-minute T1-weighted high-resolution anatomical scan with voxel size 1x1x1 mm3, TR (repetition time) 2600ms, TE (echo time) 3.02ms, flip angle 8°, FOV (field of view) 256x224 mm2, was collected for 176 slices. The experiment was carried out in three five-minute functional scans. The parameters of these functional T2*-weighted gradient echo sequences are as follows: voxel size was 3x3x3 mm3, TR (repetition time) was 2000ms, TE (echo time) was 35ms, and there were 156/159/160 measurements, each consisting of 28 slices.

3.7 fMRI data analysis:

Processing of fMRI data was performed by using AFNI software. First of all, fMRI data for each subject was preprocessed. The first step was to remove voxel time shift in each whole-brain image (159 images in run-1, 160 in run-2, and 156 in run-3). Then, realignment of the brain volumes within each run was carried out thus movement related artifacts were removed. The images were then spatially smoothed by a 6-mm-full-width-half-maximum Gaussian blur and a mask was placed on the brain excluding the skull. The mean of each voxel time series was calculated and they were standardized. Lastly, preprocessed runs were concatenated. Talairach transformation for each subject's anatomical scan was performed. The average anatomical brain was calculated by taking the mean of all 20 registered brains.

After specifying and time-smoothing the task waveforms for each subject according to the category variable, changes in the hemodynamic response produced by the different levels of color category were assessed at each voxel using deconvolution (3dDeconvolve). Similarly, additional task waveforms were specified according to the spatial separation variable and approximated hemodynamic response function by time-smoothing. And then, statistical group analysis was performed using ANOVA command and specific conditions were compared(3dANOVA). An example AFNI script including preprocessing steps and deconvolutions for subject-5 and the scripts for the group analysis can be seen in Appendix D. Some commands were rearranged in the appendix for easier tracking.

CHAPTER 4

RESULTS

We analyzed the behavioral data and brain activity data separately. Behaviorally, accuracy in color discrimination and reaction time is studied. Brain activity is studied through the changes in the BOLD signal.

4.1 Accuracy

Figure 4.1 shows the mean correct responses for each color category within each spatial display. It was found that the mean correct responses for each of six experimental conditions are above chance level (6); $t(19)$, $p < 0.0001$. It was checked if there is an effect of gender on accuracy scores. An independent samples t-test revealed no significant difference between males and females; $t(19) = -0.371$, $p = 0.715$. An additional, paired t-test was performed in order to check whether the position of the "different" color pair had an effect on performance scores; the different pairs were detected equally well both on the right and on the left; $t(19) = -1.254$, $p = 0.225$.

It can be seen in the figure that performance on discriminating within-green pair was better than discriminating cross-category pair, which was in turn better than discriminating within-blue pair. This decremental pattern appears to be in a more straight form for adjacent trials than for spatially separated trials. Moreover, for within-green and cross-category pairs, discrimination seems to be easier in adjacent trials than separated trials, but this trend is not applicable to within-blue pair, which appears to result in equally worse performance in both adjacent and separated trials.

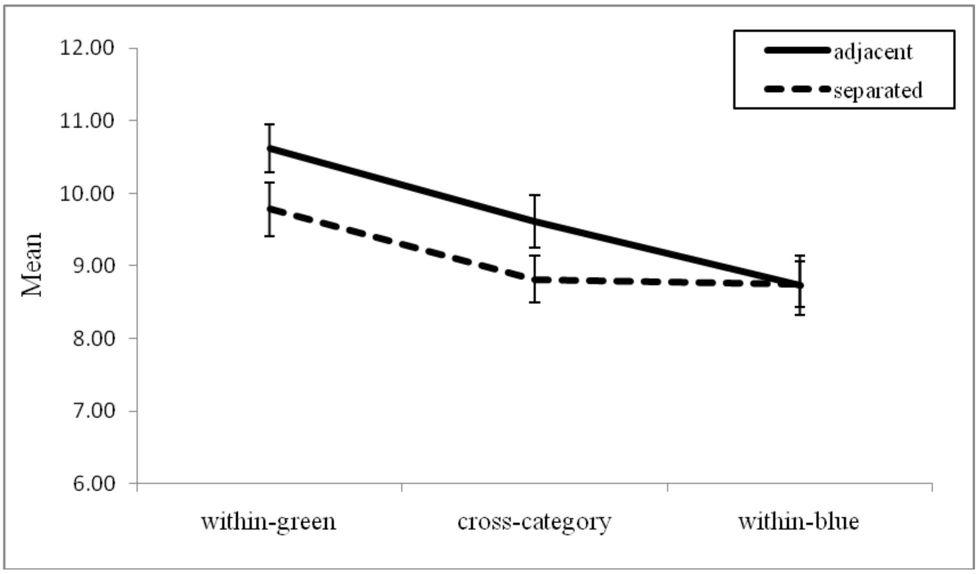


Figure 4.1: Mean Correct Responses for Each Color Category within Each Spatial Display Error Bars Show ±1 Standard Error

A repeated measures analysis of variance with two within-subject factors (color category and spatial display) revealed that the main effect of color category was significant; $F(2,38) = 26.868, \ p < 0.0001$, that the main effect of spatial display was significant; $F(1,19) = 8.278, \ p = 0.01$, and that the interaction between the two factors was not significant; $F(2,38) = 2.908, \ p = 0.067$. This means that there is an effect of color category on performance scores independent of which spatial form the color pairs were displayed in. Similarly, there is an effect of spatial display on performance scores independent of which color pair was displayed.

Comparisons between the three levels of color category indicated that within-green pair was discriminated more accurately than cross-category pair; $F(1,19) = 43.036$, $p < 0.0001$ and within-blue pair; $F(1,19) = 42.501, \ p < 0.0001$. Cross-category pair was in turn discriminated more accurately than within-blue pair; $F(1,19) = 4.587$, $p = 0.045$.

Concerning the interaction between the two factors, as Figure 4.1 demonstrates, performance scores seem to be equally better in adjacent trials than separated trials for both within-green and cross-category pairs. This trend was statistically supported; $F(1,19) = 0.008, \ p = 0.929$. This effect is still conserved between within-green and within-blue conditions; $F(1,19) = 2.874, \ p = 0.106$. On the other hand, there is a significant interaction effect between category and spatial separation variables for the cross-category and within-blue conditions as the significance value pointed; $F(1, 19) = 7.803,\ p = 0.012$. This interaction effect suggests that better performance on adjacent trials than separated trials is evident in cross-category discrimination; however, performance on adjacent trials and separated trials was equal in within-blue discrimination.

The ANOVA was followed by post hoc tests, for which Tukey's honestly significant difference was used. For the adjacently displayed trials, performance was better on within-green pair than cross-category pair; $p = 0.013$, within-green pair was also discriminated better than within-blue pair; $p = 0.0001$, and accuracy scores for cross-category pair was significantly higher than within-blue pair; $p = 0.037$. Similarly, for the categories of color pairs displayed with gaps, performance was better for within-green pair than cross-category pair; $p = 0.018$, within-green pair was also discriminated better than within-blue pair; $p = 0.01$, but accuracy scores for cross-category pair and within-blue pair was equal; $p = 1$.

Post hoc comparisons also showed that while discriminating within-green pair, the difference between performance on adjacent and separated trials was nearly significant; $p = 0.057$. For the cross-category pair, accuracy scores for adjacent and separated trials did not differ significantly; $p = 0.074$ and for the within-blue pair, equal performance was observed for adjacent colors and colors that are separated; $p = 1$.

4.2 Reaction Time

Figure 4.2 shows the mean reaction time on correct responses for each color category within each spatial display. It can be seen in the figure that performance on color discrimination was quicker for within-green pair than cross-category pair, which is in turn discriminated quicker than within-blue pair. This incremental pattern seems to be similar for both adjacently and separately displayed trials, although adjacently displayed trials seems to be discriminated faster in general.

A repeated measures analysis of variance with two within-subject factors (color category and spatial display) revealed that the main effect of color category was significant; $F(2, 38) = 15.986,\ p < 0.0001$, that the main effect of spatial display was

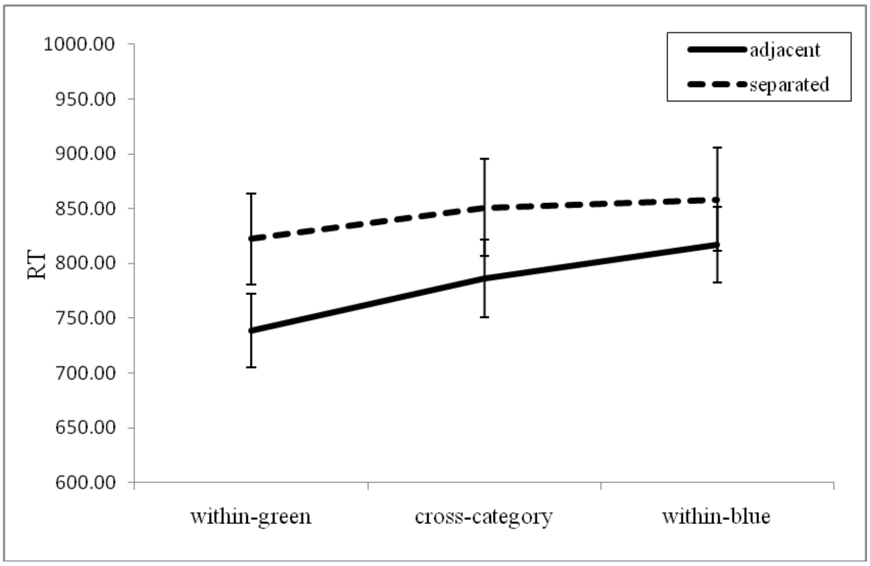


Figure 4.2: Mean Reaction Time on Correct Responses for Each Color Category within Each Spatial Display
Error Bars Show ±1 Standard Error

significant; $F(1, 19) = 12.552,\ p = 0.002$, and that the interaction between the two factors was also significant; $F(2, 38) = 4.490,\ p = 0.018$. This means that whether there is an effect of color category on performance scores depends on which spatial display the color pairs were displayed in.

Comparisons between the three levels of color category indicated that within-green pair was discriminated faster than both cross-category pair; $F(1, 19) = 12.344, p = 0.002$, and within-blue pair; $F(1, 19) = 25.689,\ p < 0.0001$. Cross-category pair was in turn discriminated faster than within-blue pair; $F(1, 19) = 4.942,\ p = 0.039$.

Concerning the interaction between the two factors, reaction time scores seems to be equally faster for adjacent trials than separated trials for both within-green and cross-category pairs. The similarity of this trend was statistically supported; $F(1, 19) = 1.750,\ p = 0.202$. The similarity of the lines for adjacent and separated trials is still conserved between cross-category and within-blue pairs; $F(1, 19) = 3.188,\ p = 0.09$. The trend for adjacent and separated trials between within-green and within-blue pairs on the other hand appears not to be parallel; the performance scores are more close for adjacent and separated trials for within-blue pair than within-green pair and this interaction effect was statistically significant; $F(1, 19) = 8.043,\ p = 0.011$.

The ANOVA was followed by Tukey's honestly significant difference post hoc tests. For the adjacently displayed trials, performance was better on within-green pair than cross-category pair; $p = 0.0005$, within-green pair was also discriminated faster than within-blue pair; $p = 0.0001$, and reaction time for cross-category pair was significantly faster than within-blue pair; $p = 0.045$. For the separately displayed trials, performance was equal on within-green pair and cross-category pair; $p = 0.07$. Within-green pair, on the contrary, was discriminated faster than within-blue pair; $p = 0.012$, but reaction times for cross-category pair and within-blue pair was equal; $p = 0.098$.

In addition, post hoc tests revealed that when within-green pair was displayed adjacently, it is discriminated faster than when displayed separately; $p = 0.0001$. The same trend is applicable to cross-category pair; $p = 0.0001$ and to within-blue pair; $p = 0.003$.

4.3 fMRI Data

For all the figures below, crosshairs are placed on activations that exceed a threshold on sagittal, axial and coronal slices on top, bottom left and bottom right pictures respectively. The red-orange-yellow activation colors indicate positive values and the blue activation colors indicate negative values; the scale for the colored activation spots is shown in Figure 4.3. The significance of the activations may differ across each statistical analysis, as specified underneath each figure. The underlay is the anatomical brain obtained by averaging structural high-resolution T1-weighted 3D scans of all 20 participants.

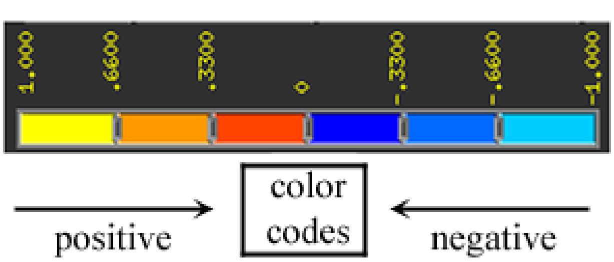


Figure 4.3: Significance scale for the colored activation spots

4.3.1 The Gap Effect: Comparison of Adjacent and Spatially Separated Trials

Figure 4.4 shows the brain activation in response to spatially separated colors minus adjacently displayed colors. The functional group data obtained by performing one-way repeated measures ANOVA with a within-subjects factor (spatial display) with two levels (spatially separated and adjacent) was overlaid on the average anatomical brain. The activation colors indicate positive values such that in these spots activation in response to separated color discrimination was greater than adjacent color discrimination.

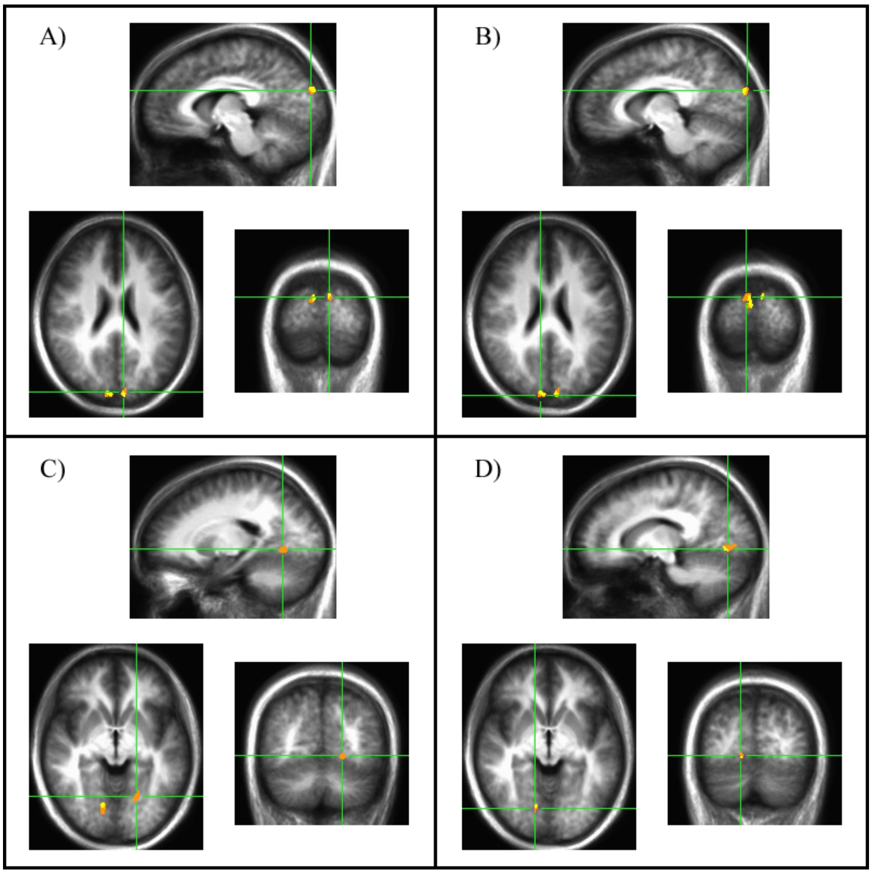


Figure 4.4: Separated vs. Adjacent color discrimination: Brain activation in response to spatially separated trials minus adjacently displayed trials;
A) Left Cuneus ($p < 0.01$, $cs = 175$ voxels, Talairach Coordinate $x = 7$, $y = 87$, $z = 23$),
B) Right Cuneus ($p < 0.01$, $cs = 175$ voxels, Talairach Coordinate $x = -8$, $y = 90$, $z = 23$),
C) Left Lingual Gyrus ($p < 0.02$, $cs = 175$ voxels, Talairach Coordinate $x = 19$, $y = 61$, $z = -1$),
D) Right Lingual Gyrus ($p < 0.01$, $cs = 175$ voxels, Talairach Coordinate $x = -13$, $y = 72$, $z = -1$).

As can be seen in Figure 4.4A and 4.4B, when color pairs were spatially separated, Cuneus was more activated bilaterally than when pairs were displayed adjacently; $p < 0.01$, cluster size $cs = 175$ voxels and Talairach Coordinate is $x = 7$, $y = 87$, $z =$

23 for the Left Cuneus and $x = -8,\ y = 90,\ z = 23$ for the Right Cuneus. Bilateral Lingual Gyrus was also found to be more active in spatially separated trials than adjacent trials; $p < 0.02,\ cs = 175$ voxels and Talairach Coordinate is $x = 19,\ y = 61,\ z = -1$ for the Left Lingual Gyrus (Figure 4.4C) and; $p < 0.01,\ cs = 175$ voxels and Talairach Coordinates is $x = -13,\ y = 72,\ z = -1$ for the Right Lingual Gyrus (Figure 4.4D).

There were no significant activations in Adjacent-Separated contrast, except for the negative translation of activations in the same areas showed in Figure 4.4.

4.3.2 The Category Effect: Binary Comparisons

The functional group data obtained by performing one-way repeated measures ANOVA with a within-subjects factor (color category) with three levels (within-green, cross-category, and within-blue) is overlaid on the average anatomical brain.

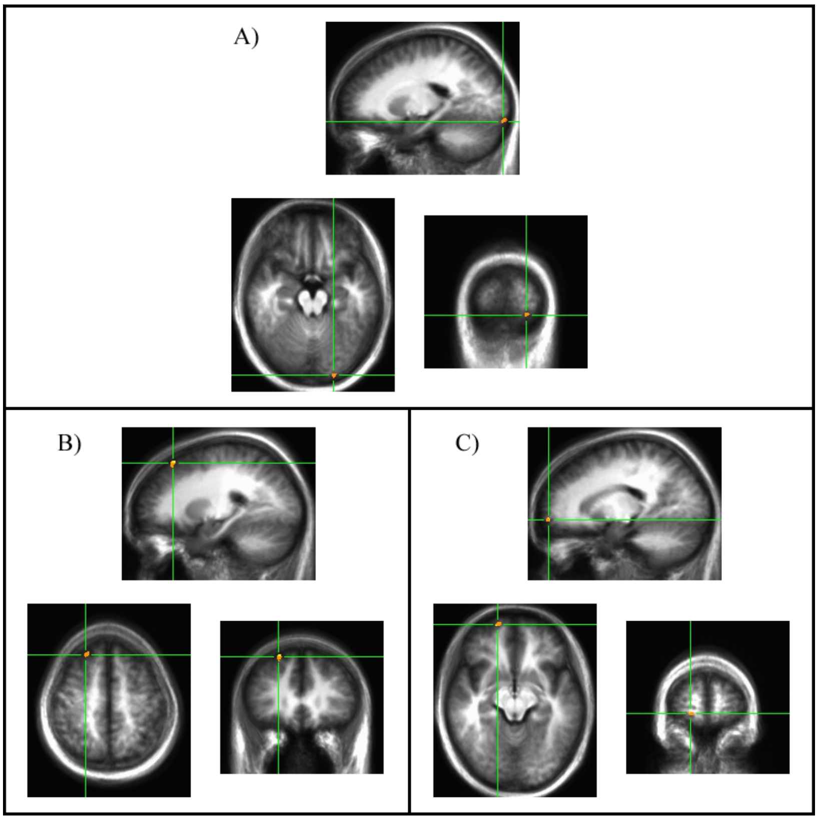


Figure 4.5: Green vs. Blue: Brain activation in response to within-green pair minus within-blue pair;
A) Left Fusiform Gyrus ($p < 0.03,\ cs = 50$ voxels, Talairach Coordinate $x = 20,\ y = 93,\ z = -13$),
B) Right Superior Frontal Gyrus ($p < 0.02,\ cs = 100$ voxels, Talairach Coordinate $x = -23,\ y = -30,\ z = 50$),
C) Right Medial Frontal Gyrus ($p < 0.02,\ cs = 50$ voxels, Talairach Coordinate $x = -17,\ y = -60,\ z = -6$).

Figure 4.5 shows the brain activation in response to within-green trials minus within-blue trials.It can be seen in Figure 4.5A that Left Fusiform Gyrus got more activated in response to within-green discrimination than within-blue discrimination; $p < 0.03,\ cs = 50$ voxels and Talairach Coordinate is $x = 20,\ y = 93,\ z = -13$. In addition, some right frontal regions activated more for within-green trials than within-blue trials; $p < 0.02,\ cs = 100$ voxels and Talairach Coordinate is $x = -23,\ y = -13,\ z = 50$ for Right Superior Frontal Gyrus (Figure 4.5B) and; $p < 0.02,\ cs = 50$ voxels and Talairach Coordinate is $x = -17,\ y = -60,\ z = -6$ for the Right Medial Frontal Gyrus (Figure 4.5C).

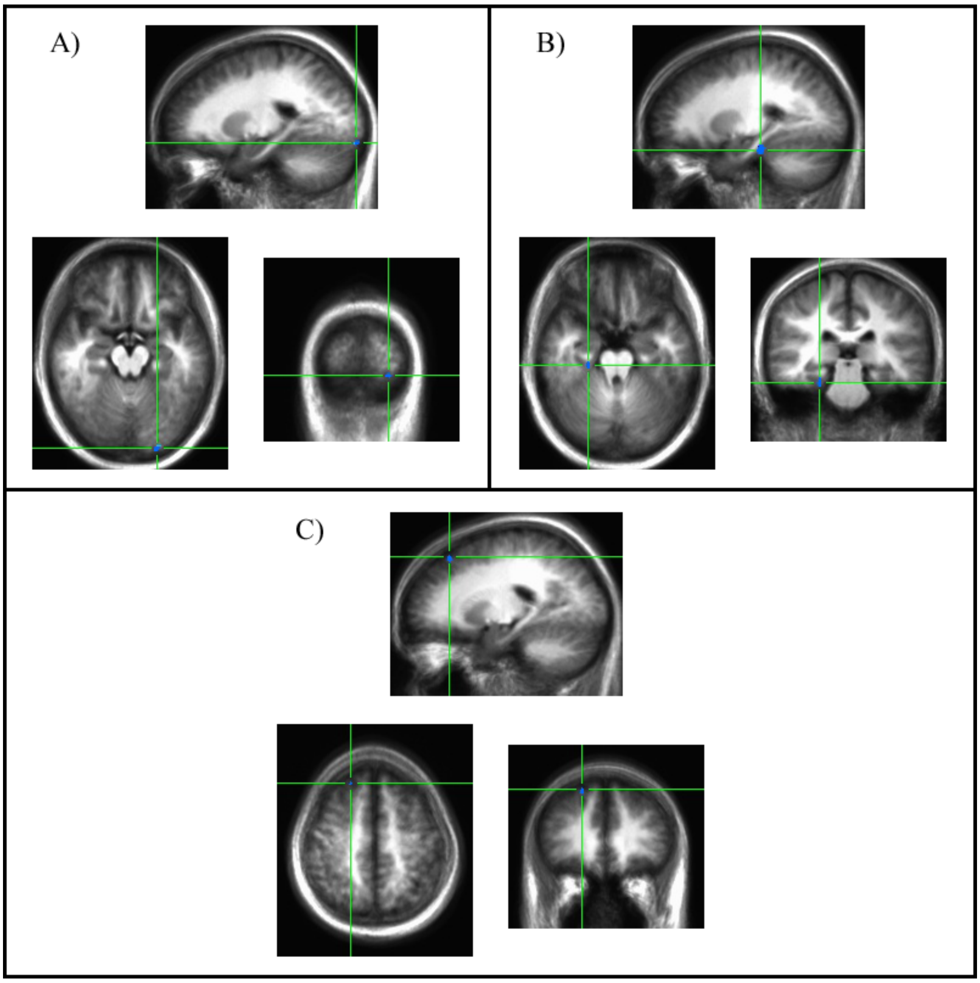


Figure 4.6: Cross vs. Green: Brain activation in response to cross-category pair minus within-green pair;
A) Left Fusiform Gyrus ($p < 0.03,\ cs = 50$ voxels, Talairach Coordinate $x = 22,\ y = 93,\ z = -11$),
B) Right Parahippocampal Gyrus ($p < 0.03,\ cs = 93$ voxels, Talairach Coordinate $x = -24,\ y = 25,\ z = -17$),
C) Right Superior Frontal Gyrus ($p < 0.03,\ cs = 25$ voxels, Talairach Coordinate $x = -20,\ y = -32,\ z = 49$).

Figure 4.6 shows the brain activation in response to cross-category pair minus within-green pair. It can be seen in Figure 4.6A that Left Fusiform Gyrus was more active in response to within-green discrimination than cross-category discrimination; $p < 0.03,\ cs = 50$ voxels and Talairach Coordinate is $x = 22,\ y = 93,\ z = -11$. Figure 4.6B demonstrates that Right Parahippocampal Gyrus was also more activated in within-green trials than cross-category trials; $p < 0.03,\ cs = 93$ voxels and Talairach Coordinate is $x = -24,\ y = 25,\ z = -17$. Increased activation for within-green pair compared to cross-category pair was also found in Right Superior Frontal Gyrus (Figure 4.6C); $p < 0.03,\ cs = 25$ voxels, Talairach Coordinate is $x = -20,\ y = -32,\ z = 49$.

Figure 4.7 shows the brain activation in response to cross-category pair minus within-green pair. As can be seen below, Left Superior Temporal Gyrus was more active in response to within-blue discrimination than cross-category discrimination; $p < 0.02,\ cs = 100$ voxels and Talairach Coordinate is $x = 42,\ y = -7,\ z = -21$.

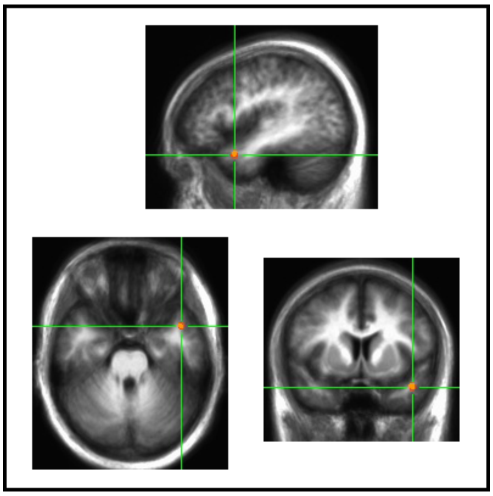


Figure 4.7: Blue vs. Cross: Brain activation in response to within-blue pair minus cross-category pair; Left Superior Temporal Gyrus ($p < 0.02,\ cs = 100$ voxels, Talairach Coordinate $x = 42,\ y = -7,\ z = -21$).

4.3.3 The Category Effect: Ternary Comparisons

Figure 4.8 shows the brain activation in response to within-green pair minus within-blue and cross-category pairs. It can be seen in Figure 4.8A that Left Fusiform Gyrus was more activated in response to within-green discrimination than within-blue and cross-category discrimination; $p < 0.025,\ cs = 75$ voxels and Talairach Coordinate is $x = 23,\ y = 93,\ z = -13$). Figure 4.8B shows greater activation for within-green trials than within-blue and cross-category trials in Right Superior Frontal Gyrus; $p <$

0.02, $cs = 125$ voxels and Talairach Coordinate is $x = -20,\ y = -32,\ z = 49$. Figure 4.8C represents more activation in Right Parahippocampal Gyrus for within-green pair than for within-blue and cross-category pairs; $p < 0.045,\ cs = 75$ voxels and Talairach Coordinate is $x = -25,\ y = 25,\ z = -17$.

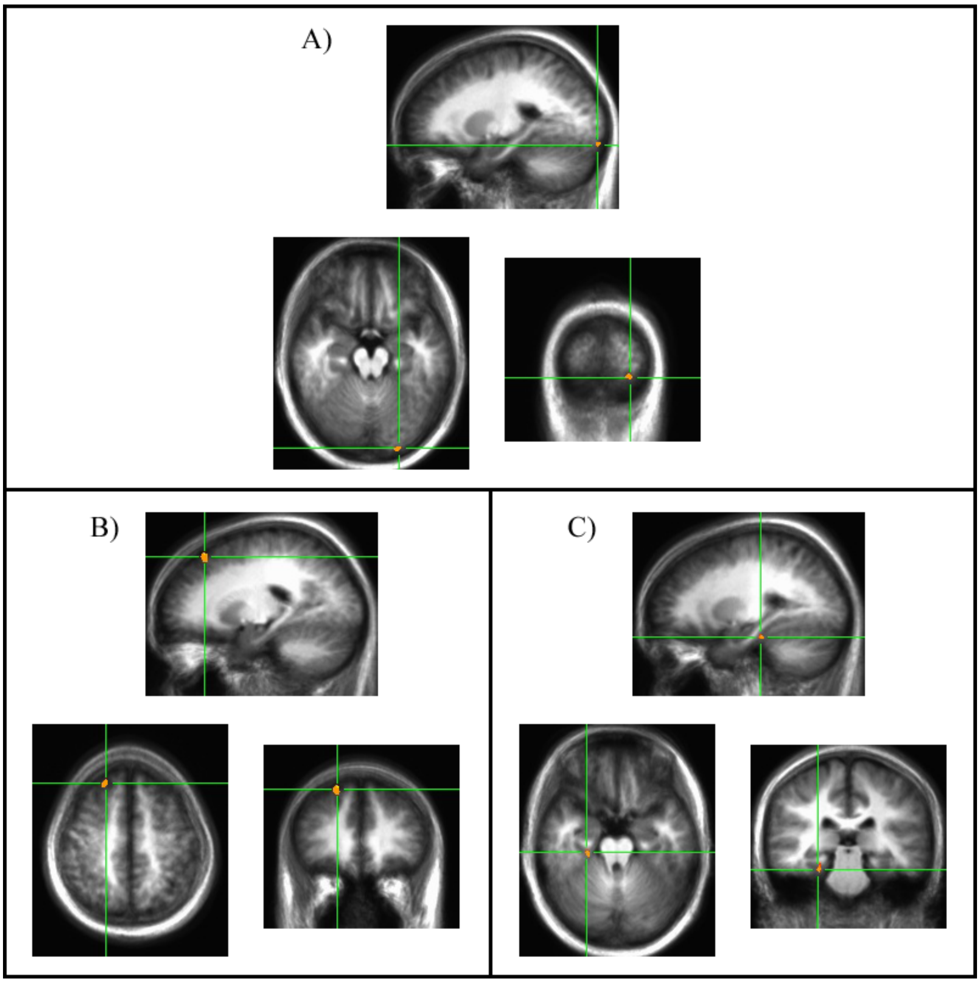


Figure 4.8: Green vs. Blue Cross: Brain activation in response to within-green pair minus within-blue and cross-category pairs;
A) Left Fusiform Gyrus ($p < 0.025,\ cs = 75$ voxels, Talairach Coord $x = 23,\ y = 93,\ z = -13$),
B) Right Superior Frontal Gyrus ($p < 0.02,\ cs = 125$ voxels, Talairach Coord $x = -20,\ y = -32,\ z = 49$),
C) Right Parahippocampal Gyrus ($p < 0.045,\ cs = 75$ voxels, Talairach Coord $x = -25,\ y = 25,\ z = -17$).

Figure 4.9 shows the brain activation in response to within-blue pair minus within-green and cross-category pairs. It can be seen in Figure 4.9A that Left Superior Temporal Gyrus was more active in response to within-blue discrimination than within-green and cross-category discrimination; $p < 0.045,\ cs = 25$ voxels and Talairach Coordinate is $x = 42,\ y = -7,\ z = -21$. Figure 4.9B shows negative values, i.e. less activation for within-blue trials than within-green and cross-category trials in Left Fusiform Gyrus; $p < 0.04,\ cs = 25$ voxels and Talairach Coordinate is $x =$

20, $y = 95$, $z = -12$). In addition, Right Medial Frontal Gyrus; $p < 0.025$, $cs = 25$ voxels and Talairach Coordinate is $x = -17$, $y = -60$, $z = -6$ (Figure 4.9C) and Left Medial Frontal Gyrus got less activated in within-blue trials than within-green and cross-category trials; $p < 0.04$, $cs = 25$ voxels and Talairach Coordinate is $x = 10$, $y = -42$, $z = -79$ (Figure 4.9D).

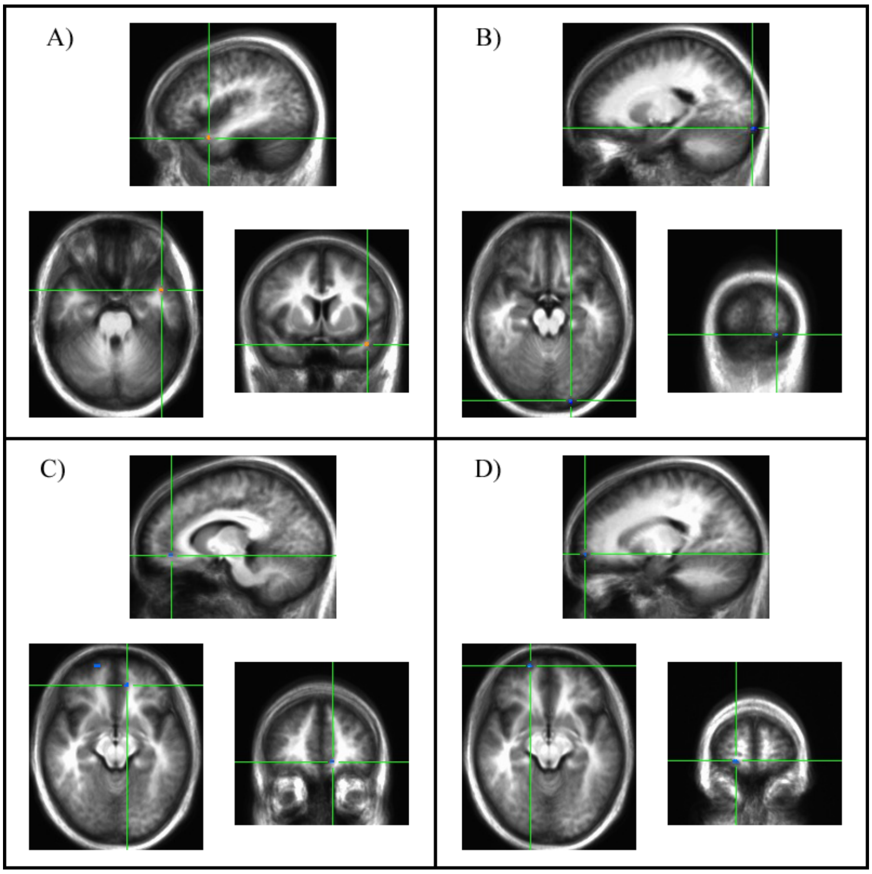


Figure 4.9: Blue vs. Green Cross: Brain activation in response to within-blue pair minus within-green and cross-category pairs;
A) Left Superior Temporal Gyrus ($p < 0.045, cs = 25$ voxels, Talairach Coord $x = 42$, $y = -7$, $z = -21$),
B) Left Fusiform Gyrus ($p < 0.04$, $cs = 25$ voxels, Talairach Coord $x = 20$, $y = 95$, $z = -12$),
C) Left Medial Frontal Gyrus ($p < 0.04$, $cs = 25$ voxels, Talairach Coord $x = 10$, $y = -42$, $z = -7$),
D) Right Medial Frontal Gyrus ($p < 0.025$, $cs = 25$ voxels, Talairach Coord $x = -17$, $y = -60$, $z = -6$).

Finally, Figure 4.10 shows brain activation in response to cross-category pair minus within-category (within-green and within-blue) pairs. As can be seen in Figure 4.10A, Right Precuneus activation was greater in within-category discrimination than cross-category discrimination; $p < 0.03$, $cs = 50$ voxels and Talairach Coordinate is $x = -2$, $y = 49$, $z = 32$. Left Superior temporal Gyrus was also more activated for within-category trials than cross-category trials; $p < 0.03$, $cs = 75$ voxels and Talairach Coordinate is $x = 42$, $y = -6$, $z = -19$.

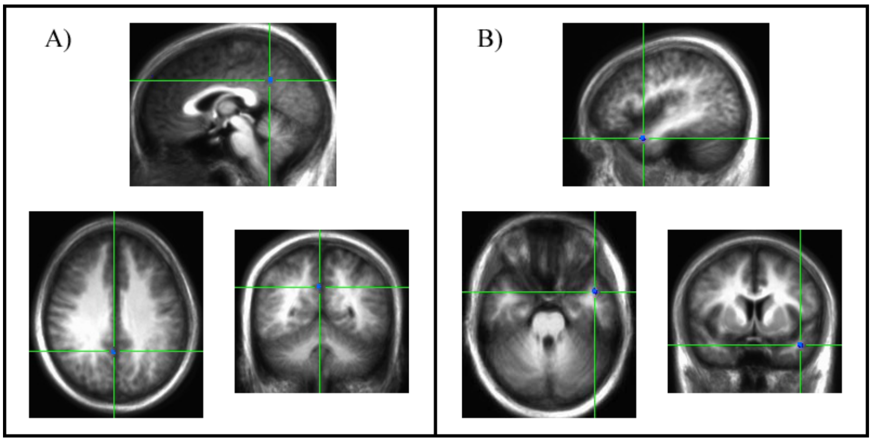


Figure 4.10: Cross vs. Within: Brain activation in response to cross-category pair minus within-green and within-blue pairs;
A) Right Precuneus ($p < 0.03,\ cs = 50$ voxels, Talairach Coordinate $x = -2,\ y = 49,\ z = 32$),
B) Left Superior Temporal Gyrus ($p < 0.03,\ cs = 75$ voxels, Talairach Coordinate $x = 42,\ y = -6,\ z = -19$).

At the end of the binary comparisons, it is worthy of note that the exclusive discrimination of blue pair and green pair versus discrimination of cross-category with respect to green versus blue color discrimination are represented at different cortical locations that participate in several high-level cognitive tasks. It seems as if single color discrimination and multiple color discrimination are handled differentially in the brain. It is also important to note that significant activation differences observed between conditions in the case of ternary comparisons were grounded on the significant activation differences found in binary comparisons (see Figure 4.11). Elaborately, for the Blue-GreenCross contrast, negative bilateral Medial Frontal activation resulted from positive Green-Blue difference in the same areas, positive Left Superior Temporal activation arose from positive Blue-Cross activation in the same region, and negative Left Fusiform activation proceeded from positive Left Fusiform activation in Green-Blue difference. Similarly, for the Green-BlueCross contrast, positive Right Parahippocampal activation originated in negative Cross-Green difference in the same region, positive Left Fusiform and Right Superior Frontal activations were based on both positive Green-Blue difference and negative Cross-Green activation in these areas. Most importantly, for the Cross-Within contrast, negative Right Precuneus activation took root from negative Right Precuneus activation in Cross-Green difference and negative Left Superior Temporal difference had its source in positive Blue-Cross difference in the same region.

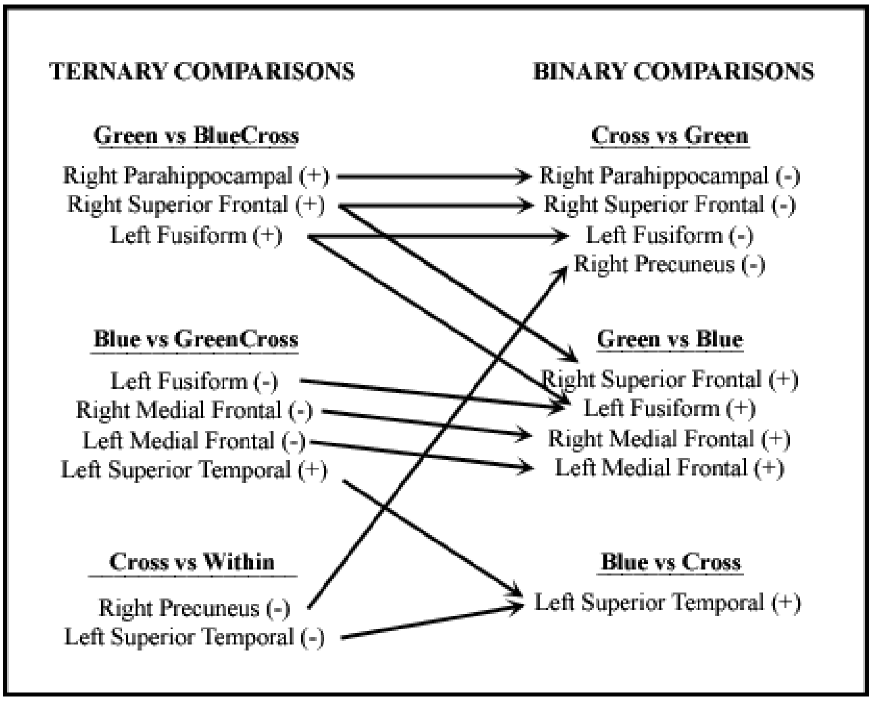


Figure 4.11: Significant Activations in Ternary Comparisons Being Grounded on Significant Activations in Binary Comparisons Pluses and Minuses into Parentheses Show Direction of the Given Difference at Each Brain Region

The activation differences in anatomical structures were summarized in Table 4.1. The localizations and characteristics of these differences can be listed as follows:

Cuneus: Located in the occipital lobe. Reflects differential activation in separated condition compared to adjacent condition.

Lingual Gyrus: Located in the occipital lobe. Extends to the temporal region. Reflects differential activation in separated condition compared to adjacent condition.

Fusiform Gyrus: Located in the temporal lobe. Activation is mainly present in cross versus green and green versus blue contrasts; therefore it is observed in ternary comparisons: green versus blue and cross and blue versus green and cross.

Superior Frontal Gyrus: Located in the frontal lobe. Activation is primarily present in cross versus green and green versus blue contrasts; therefore it is seen in ternary comparisons: green versus blue and cross and blue versus green and cross.

Medial Frontal Gyrus: Located in the frontal lobe. Activation is basically present in green vs blue contrast; it is seen in ternary comparison blue versus green and cross.

Superior Temporal Gyrus: Located in the temporal lobe. Activation is mainly present in blue versus cross contrast; therefore it is observed in ternary comparisons: blue versus green and cross and cross versus within (green and blue).

Parahippocampal Gyrus: Located in the temporal lobe, surrounding the subcortical structure hippocampus. Activation is primarily present in cross versus green contrast; therefore it is seen in ternary comparison green versus blue and cross.

Precuneus: Located in the parietal lobe. Activation is mainly present in cross versus green contrast; therefore it is seen in ternary comparison cross versus within (green and blue).

Table 4.1: Summary of fMRI Results: Active Brain Regions for Each Contrast with significance values (p), cluster size (the number of contiguous active voxels), and Talairach Coordinates (x,y,z)

Contrast	**Brain Region**	**p**	**Cluster Size**	**(x,y,z) Coordinate**
Separated - Adjacent	L Cuneus (BA19)	.01	175	7, 87, 123
	R Cuneus (BA19)	.01	175	-8, 90, 23
	L Lingual Gyrus (BA19)	.01	25	19, 61, -1
	R Lingual Gyrus (BA18)	.01	175	-13, 72, -1
Green - Blue	L Fusiform Gyrus (BA18)	.03	50	20, 93, -13
	R Superior Frontal Gyrus (BA8)	.02	100	-23, -30, 50
	L Medial Frontal Gyrus	.05	15	11, -43, -7
	R Medial Frontal Gyrus	.02	50	-17, -60, -6
Cross - Green	L Fusiform Gyrus	.03	50	22, 93, -11
	R Parahippocampal Gyrus (BA35)	.03	93	-24, 25, -17
	R Superior Frontal Gyrus (BA8)	.03	25	-20, -32, 49
	R Precuneus (BA7)	.04	15	-3, 50, 34
Blue-Cross	L Superior Temporal Gyrus	.02	100	42, -7, -21
Green - BlueCross	L Fusiform Gyrus	.025	75	23, 93, -13
	R Superior Frontal Gyrus (BA8)	.02	125	-20, -32, 49
	R Parahippocampal Gyrus (BA35)	.045	75	-25, 25, 17
Blue - GreenCross	L Fusiform Gyrus (BA18)	.04	25	20, 95, -12
	L Superior Temporal Gyrus	.045	25	-42, -7, -21
	L Medial Frontal Gyrus	.04	25	10, -42, -7
	R Medial Frontal Gyrus	.025	25	-17, -60, -6
Cross - Within	R Precuneus (BA7)	.03	50	-2, 49, 32
	L Superior Temporal Gyrus	.03	75	-42, -6, -19

CHAPTER 5

GENERAL DISCUSSION

Categorical perception implies physically equal but perceptually biased distances between color pairs. The most critical outcome of the present results is that despite the unequal performance on color discrimination, the resulting pattern challenges the typical categorical color perception (CCP) pattern. Our results are discussed below in terms of behavioral findings as well as brain activity findings. Overall, among the hypotheses that we have studied H1, H2, H4, and H5 are confirmed.

5.1 Behavioral Results

The prediction that performance on color discrimination throughout green-blue region of the color spectrum would yield a decrementing pattern from green region to blue region was supported. Although the CIE LCh color metric is physically based and supposed to be perceptually uniform, performance on discriminating equally distant pairs defined in this space was not uniform. Within-green discrimination was the most accurate, cross-category discrimination was at intermediate level and within-blue discrimination was the least accurate. In order to reveal a typical categorical effect, the accuracy scores should be equally worse for within-green and within-blue pairs than the cross-category pair; but this was not the case. Somehow, discrimination gets more difficult as colors move towards blue portion of the green-blue region. The reaction time results are predominantly in line with the accuracy results. Within-green discrimination was the fastest, cross-category discrimination was at intermediate level and within-blue discrimination was the slowest. Reaction times, similarly to the accuracy results, revealed a pattern unyielding with the typical categorical effect.

In addition, the other behavioral prediction that adjacently displayed color pairs would be discriminated better than spatially separated pairs was also supported. In this sense, discriminating color pairs having a gap between them is more difficult than contiguously presented pairs. Adjacent display advantage over spatially separated colors was also found in RT measures. Although our results are in line with our expectations, elaboration of our findings with respect to those of Danilova and Mollon (2006) is not easy, due to differences in the set-up of stimulus displays. Danilova and Mollon (2006) concluded that instead of presenting color pairs adjacently, having a particular sized spatial separation between them would yield maximum performance scores. However, there is a central detail in the experiment that needs to be focused while evaluating the conclusions. The color pairs in the above cited study were presented upon a hypothetical circle, the radius of which is 5° of visual angle. Our stimulus display is not similar to the Danilova and Mollon (2006) study because we used colors side by side extending from a leftmost position to a rightmost position spanning a visual angle of either 4.6 (adjacent condition) or 6.4 (separated condition) degrees. When the color pairs were presented adjacently, there were four contiguous squares forming one rectangle on the screen, the rightmost or the leftmost of which was containing the different pair. In this case, the visual angle between the center of the differently-colored part of rectangle and the center of the closest square was 3°. When the color pairs were presented separately, there were four discrete squares on the screen, the rightmost or the leftmost of which was containing the different pair. In this case, the visual angle between the center of the differently-colored square and the center of the closest square was 4.3° of visual angle. Therefore the discrepancy in the visual angle in between the adjacent and separated conditions might have been a confounding factor in our results.

Concisely, when the distances between the stimuli and especially the width of the stimuli range were properly calculated, rather than superficially grouping conditions as adjacent and separated, the interpretation of the results with reference to a similar experiment would be more precise. In the adjacent condition of the present experiment, in which performance was remarkably better, the width of the display range (4.6°) is close to the width of the reference range and the spatial distance between the centers of the pairs (3°) was also coherent with the proposed distance in order to attain optimal performance. Therefore, it may be the case that the radius of the display area and the distance between centers of color pairs in terms of visual angle determines the level of performance, not whether having a spatial gap between them.

5.2 Brain Activity in Terms of fMRI BOLD Response

While the subjects were performing the color discrimination task, the signal change their brain was measured and different conditions were compared based on the hypotheses. The effect of color category and the effect of spatial display on brain activity were evaluated independently.

5.2.1 Adjacent Versus Spatially Separated Color Discrimination

When the color pairs were displayed adjacently, discrimination performance was both faster and more accurate relative to when they were displayed separately. In other words, discriminating spatially separated colors was more difficult. Therefore, it is reasonable to assume that spatial separation requires more neural resources for color discrimination. Due to this, brain activation differences between adjacent and spatially separated colors were expected. Greater bilateral activations in Cuneus and Lingual Gyrus in response to spatially separated pairs than adjacently displayed may be indicators of more resources required.

Results of an fMRI study on alertness training (Thimm, Fink, Küst, Karbe, & Sturm, 2006) suggest that the activations in these areas are related to visuospatial attention. Thimm et al. (2006) trained neglect patients on an alertness task for a three-week period and they distinguished between neural responses to spatial attention and alertness. Before the training period, activation in bilateral Cuneus was found in response to spatial attention without alertness and activation in Right Lingual Gyrus was found in response to spatial attention with alertness. After three-week training, activation in bilateral Cuneus was found to be increased for alertness and spatial attention with alertness. Additionally, after four non-training weeks, brain activations were compared to the just-after-three-weeks scan; activation in bilateral Cuneus decreased for spatial attention with alertness and only alertness, Left Lingual Gyrus activation decreased for spatial attention with alertness and Right Lingual Gyrus activation decreased for alertness. Therefore, it was concluded that these areas are responsive when the behavioral task is attention-demanding and entails alertness.

Furthermore, in a speed discrimination experiment (Sunaert, Hecke, Marchal, & Orban, 2000), bilateral activations in Cuneus and Lingual Gyrus was found when attention component was dissociated from other processes.

In the light of these studies, the present results showing bilateral Cuneus and Lingual Gyrus activations point out that more resources required for the spatial separation of color pairs is likely due to attention-based processes.

5.2.2 Activations Attributed to Categorical Color Perception

The involvement of the Left Fusiform Gyrus in color processing is well documented (e.g. Zeki & Marini, 1998; Simmons et al., 2007); also the color-sensitive area in the visual cortex, namely V4, is positioned in the Fusiform Gyrus (Zeki et al., 1991). Therefore, negative Left Fusiform difference in Cross-Green contrast and positive Left Fusiform difference in Green-Blue contrast may be the indicator of differential processing of green pair in comparison to cross-category pair and blue pair. In addition, the location of the activation suggests a low-level visual difference between green and the other two color categories. In this respect, it can be argued that if this area responds differently to different color categories, then Blue-Cross contrast should have induced activation in the Left Fusiform. One possible explanation for the presence of activation difference in this area for Green-Blue and for Cross-Green comparisons but the absence of activation difference in the same area for Blue-Cross comparison could be based on hue mapping in occipital lobe as revealed by experiments on macaque visual cortex[1] . It was found that both striate (Xiao et al., 2007) and extrastriate (Xiao et al., 2003) cortices contain hue-selective neurons exhibiting a positive relationship between their spatial locations on the cortex and the distance between color hues they are tuned. A similar color tuning pattern is evident in later

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[1] It is acceptable to address to macaques' visual cortex because their visual system functions alike human vision to a large extent (Komatsu et al., 1992)

visual areas such as V4 (Tanigawa, Lu, & Roe, 2010). These neuron clusters peaking in response to different hues overlap to some degree depending on which hues they represent. Considering the different amounts of overlap between the clusters, it can be inferred that green-selective neurons may be spatially more apart from blue-selective and cross-selective clusters; conversely, blue-selective and cross-selective clusters may be relatively closer to each other so as not to result in significant activation difference for Blue-Cross contrast.

In addition, greater right Superior Frontal activation in response to green pair than both blue and cross-category pairs corresponds to Brodmann Area 8 or Frontal Eye Field (FEF). This area was known to be involved in visual processing in terms of controlling saccades (Bruce, Goldberg, Bushnell, & Stanton, 1985). It was demonstrated that V4 activity increased by stimulating FEF neurons so providing a saccadic advantage (Moore & Armstrong, 2003). The role of FEF in visual tasks was also investigated excluding eye movements. In a TMS study (O'Shea, Muggleton, Cowey, & Walsh, 2004), FEF functioning was suppressed and it was observed that this suppression impaired visual discrimination performance and the impairment was independent of saccade operation. Another TMS study[2] dissociating the visual role of FEF from its motor involvement, showed that suppression of right FEF activity caused bilateral decreases in the firing of extrastriate cortex (Silvanto, Lavie, & Walsh, 2006). In addition, activation in this area was found to be correlated with task performance. In an object recognition task, correct trials induced stronger activation in the FEF than incorrect trials (Bar et al., 2006).

Similarly, macaque monkeys' hits and misses in a target detection task were predicted by signal magnitudes recorded from FEF neurons (Thompson & Schall, 1999). As the present behavioral data suggested, green pair was discriminated more accurately than both blue and cross-category pairs and blue pair was discriminated more accurately than cross-category pair. However, the difference between correct responses for green pair and the other two pairs was statistically more significant ($p < 0.0001$) than the difference between correct responses for blue and cross-category pairs ($p < 0.045$), which approached non-significant values. Thus, considering the positive relationship between accuracy scores and FEF activation, it would be an expected result that this

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[2] This study measured participants' phosphene thresholds in visual areas while eyes were closed.

area was activated stronger for green trials than both blue and cross-category trials, but no activation difference in FEF was found for Blue-Cross contrast. Besides, the top-down influence of this area on earlier visual areas (e.g. Bar et al., 2006) introduces the likelihood that the Left Fusiform activation exhibiting the same pattern as the Superior Frontal activation, i.e. presence of greater activation in green trials in comparison to blue and cross-category trials but absence of activation difference in Blue-Cross comparison, may be modulated by FEF activity.

On another front, it seems plausible to state that the Cross-Within contrast reflects the neurological marker of categorical color perception by means of expressing activation differences in response to cross-category pair versus within-category pairs. As mentioned earlier, for the Cross-Within contrast, negative Right Precuneus activation took root from negative Right Precuneus activation in Cross-Green difference and negative Left Superior Temporal difference had its source in positive Blue-Cross difference in the same region. The activations found in these two anatomical regions were likely to represent two distinct processing differences; in other words, Cross-Within comparison corresponds to simultaneous demonstration of two independent contrasts rather than indicating categorical perception. This assertion is behaviorally reasonable as well. Since cross-category pair was discriminated faster and more accurately than within-blue pair, but it was discriminated slower and less correctly than within-green pair, behavioral differences observed in the former comparison can be said to have a different characteristic than the behavioral differences observed in the latter comparison. In this regard, it can be assumed that there are separate neural processes underlying these distinct behavioral differences.

However, these differences might also be attributed to confounding factors that differ between contrasts. These factors, namely memory requirement or task difficulty will be addressed in the sections below.

5.2.3 Activations Related to Confounding Factors: Memory

The anterior portion of the Superior Temporal Sulcus, which is anatomically close to the present activated area, was identified as a color-responsive area in macaque cortex (Katsuyama et al., 2010). The finding that anterior STS lesions in macaques leaded to deterioration in performance during color discrimination supports the role of this region in color perception (Aggleton & Mishkin, 1990). Furthermore, results of an early single-cell recording study (Fuster & Jervey, 1982) pointed memory-related activations in this region during a color matching task. Monkeys were first presented with a single color on the screen, which was followed by a delay period, and then, they were presented a set of colors among which they chose the same color as the previous one. Many neurons located to lower divisions of STS showed color-related activations while the colors were on the screen, but anterior portion of the STS showed permanent activation while monkeys were keeping the percept fresh. The delay-period activation in the absence of color stimuli, in addition to activations in response to on-line color stimuli, in the anterior part designates color memory. Therefore, the activation for Blue-Cross contrast in the anterior Superior Temporal Gyrus may be the pointer of enhanced memory for the blue pair. It could also be a difficulty-level-dependent activation, especially when the longer reaction time for blue discrimination was taken into account. More importantly, this activation difference was also observed in cross versus within comparison. It is worth to note that the negative activation for Cross-Within contrast was caused by the difference between blue and cross-category trials, and the activation difference had nothing to do with green trials. If binary comparisons were not taken into consideration, then this difference interpreted as color-related memory would have been declared as "categorical perception".

Precuneus is also known to be responsive to memory-related processes. In a memory test, when participants properly remembered previously presented paintings, right Precuneus activation was stronger and peaked earlier than when they correctly detected familiar but novel paintings (Wiesmann & Ishai, 2008). Right Precuneus was also found to be activated stronger in visuospatial task than non-spatial task in the case of high performance, so better visuospatial performance associated with greater levels of Precuneus activity, supporting the role of Precuneus in spatial working memory (Wallentin, Roepstorff, Glover, & Burgess, 2006).

Another memory-based difference, this time between green and cross-category -rather than blue and cross category- colors was marked by negative right Parahippocampal activation in Cross-Green comparison, with an identical direction and similar content to the right Precuneus difference. Parahippocampal Gyrus was demonstrated to be involved in the process of correct recall in both verbal (Daselaar et al., 2001) and visual (Wiesmann & Ishai, 2008) retrieval tasks. The location of the present difference corresponds to BA35, the Perirhinal cortex, which is found to be an important structure for visual discrimination in terms of both perception and memory (Murray & Richmond, 2001; Bussey, Saksida, & Murray, 2003). In 2001, Kesner, Ravindranathan, Jackson, Giles, and Chiba trained rats on a visual recognition task in which the subjects were presented with repeated or new objects. After the training, behavioral reactions were formed in response to the repeated and new objects, then, perirhinal cortices of the rats were removed. It was observed that Perirhinal removal caused permanent failure to recognize the objects. Focusing on the role of this region in visual tasks, the better performance on discriminating green pair than cross-category pair may be related to enhancement of perception and memory by Parahippocampal or Perirhinal functioning.

5.2.4 Activations Related to Confounding Factors: Task Difficulty

As the present results suggested, physically equal distances between color pairs did not ensure perceptually equal distances. Although there is a 10 LCh units distance between hue angles of pairs for each color, discrimination performance decreased from green region to blue region. In other words, color category as the manipulated variable is accompanied by another, in fact a confounding variable, which will be called “difficulty level confound” hereafter. Therefore, any activation differences between three levels of the independent variable could be the index of the effect of either being from different color categories, i.e. the intended observation, or having a different degree of difficulty.

In an fMRI study (Lewandowska, Piatkowska-Janko, Bogorodzki, Wolak, & Szelag, 2010), participants’ neural responses were measured while they were performing a temporal order judgment task. Trials were grouped into three categories in terms of difficulty level: easy, moderate, and difficult. Accuracy and reaction time are said to be the basis of measuring task difficulty when difficulty level is manipulated (Barch et al., 1997; Lewandowska et al., 2010; Rinne, 2010; Gilbert, Bird, Frith, & Burgess, 2012). Although Lewandowska et al. (2010) employed a temporal processing task, which was in a different modality than the present study, the outcome of the results that low levels of difficulty was associated with increased activation in brain areas specific to the task and high levels of difficulty was associated with increased activation in brain areas that are unrelated to the specific task but related to the attentional processes, can offer a standpoint for evaluating difficulty effect within different modalities. Consequently, for our study, activation increases in brain areas that are specific to color processing could be resulted from lower levels of difficulty and any activation increases in attention sites of the brain could be resulted from increased task difficulty. According to the present behavioral results, activation increases for green color can be related to the relative easiness of green discrimination and the resulted regions are likely to be color-responsive. On the other hand, activation increases for blue color can be related to the relative difficulty of blue discrimination and the resulted regions are likely to be attention-related.

In a serial reaction time task, participants were required to detect a fixation cross just above one of four squares on the same screen and press the corresponding button (Oishi et al., 2005). After some time, their performance improved and reaction times were reduced. It was demonstrated that the amount of behavioral improvement was predictable from Precuneus activation; greater improvement, i.e. greater reduction in RT, was associated with activation increase in Precuneus. Similarly, in an object recognition task, displaying an object second time leaded to quicker and more correct responses than the first display, which in turn leaded to greater medial Precuneus activation (Korsnes, Wright, & Gabrieli, 2008). In addition to reflecting behavioral improvement, the same region was associated with the amount of resources spent for the task; Precuneus activation decreased when more resources were needed for task performance. Another experiment asked participants to solve Sudoku puzzles with two levels of difficulty (Jin et al., 2012). While solving the difficult version of Sudoku, in which both left-to-right and top-to-bottom dimensions needed to be paid attention, Precuneus activation was further decreased than while solving easier version of the puzzle, in which only one dimension, left-to-right or top-to-bottom, needed to be paid attention.

In our study, right Precuneus activation is observed in Cross-Within contrast due to differential activity in response to green discrimination compared to cross-category discrimination. This area was associated with behavioral improvement and better performance. When the significantly higher accuracy and RT scores on green pair was considered, this activation increase can be explained by low levels of difficulty so high levels of performance for green color.

Rolls, Grabenhorst, and Deco (2010) proposed a network model focusing on the relationship between decision confidence and behavioral and neuronal responses. First, the term discriminability was defined in terms of difficulty level, such that discriminability and difficulty were negatively correlated. Decision confidence, on the other hand, was positively related to discriminability. Similarly, BOLD response was found to be positively related to discriminability. In other words, lower levels of difficulty was associated with higher levels of discriminability, thus higher levels of decision confidence and higher levels of neuronal activity. They conducted experiments, in which easier trials (faster response times, greater percentage of correct responses, and higher discriminability) induced greater activations in medial prefrontal cortex compared to difficult trials. The location of reported brain region is very close to the Medial Frontal area covered in the present results as the activation difference in Green-Blue contrast. Therefore, together with more accurate responses, faster reaction times, so higher discriminability for green pair than blue pair, greater activation of bilateral Medial Frontal area could be the sign of more confident perceptual decisions while discriminating green pair than blue pair. Taking the behavioral results that green-blue difference was the most prominent among the differences between three levels of the category variable into account, it would be plausible to argue that participants differentiated between two particular shades of green more confidently than two particular and equally distant shades blue.

5.2.5 Limitations of the present study

The horizontal color display we chose for stimulus presentation is not compatible with the circular color display of the Danilova and Mollon (2006) study, which complicates driving conclusions from the adjacent versus separated color discrimination conditions in our study. In the spatially separated condition of the present experiment, although the gap between color pairs, which corresponds to 1.2° of visual angle, seems optimal for obtaining highest performance, the width of the display range (6.4°) did not match the width of the display range in the reference experiment (5°), also the distance between centers of the pairs (4.3°) slightly exceeded the suggested interval. In addition, to obtain the maximum performance scores, the gap between the nearest borders of pairs should have been 1°-2° and the visual angle between the centers discriminated pair should have been 3°-4°, after which performance started to decline. The visual angle relating to gaps and centers of colors to be discriminated should be studied further.

CHAPTER 6

CONCLUSION

The present study was designed mainly to investigate changes in brain activity in response to discrimination of color pairs from three different categories. One of the pairs was specified as cross-category pair by choosing one color from green side of the green-blue boundary and the other color from blue side. The other two pairs were featured as within-category pairs by choosing two shades of green for within-green pair and two shades of blue for within-blue pair. Crucially, the pairs varied only in hue dimension and the physical distance between each of three pairs was set to 10 degrees in CIE LCh space.

Before anything else, analyzing within-green and within-blue pairs independently from each other, instead of joining them together as within-category, provides means for evaluating the influence of color category on discrimination performance and on neural activity more effectively.

According to the concept of categorical color perception, cross-category discrimination has a perceptual advantage over within-category discrimination. However, according to our findings, even though perceptual distances between color pairs were normalized using physically equal distances, performance was not uniform in the green-blue region. The typical pattern of categorical color perception claims that performance on category boundary is markedly higher than performance within either side of the boundary; but the present behavioral data did not support this trend. In other words, discriminating cross-category pair should have yielded better performance than both within-green and within-blue pairs, but the results revealed that the difference between cross-category trials and within-green trials does not have the same characteristic as the difference between cross-category trials and within-blue trials. While cross-category discrimination was better than within-blue discrimination, it was worse than within-green discrimination; there is a systematic decline in performance throughout the green-blue region. In short, the present evidence challenges the classical categorical perception pattern.

Perhaps the findings could be explained by confounds involving unbalanced difficulty levels, or different memory requirements between the three categories. The neural bases of these confounds were demonstrated in the present fMRI results. Consistently with their behavioral counterparts, Green-Blue contrast activated Medial Frontal regions, which was associated with more confident decisions due to the low levels of difficulty (Rolls et al., 2010), Green-BlueCross contrast revealed activation in Superior Frontal region FEF, which was associated with enhanced performance (Thompson & Schall, 1999; Bar et al., 2006) and Green-Cross contrast activated Parahippocampal region, which was associated with behavioral success (Wiesmann & Ishai, 2008). Left Superior Temporal activation in Blue-Cross comparison points a difference in perceptual memory (Fuster & Jervey, 1982) between blue and cross-category; therefore, it may indicate a process in which participants were trying to keep the stimuli fresh in mind. Right Precuneus activation in Cross-Green comparison points a task-related spatial working memory (Wallentin et al, 2006); therefore, it may indicate a process in which participants were keeping the position of the different pair in mind, due to having already discriminated the green pair.

These activations suggest the involvement of higher-level, predominantly difficulty-related processes. The only difference that can be regarded as a low-level effect is the Fusiform activation in Green-BlueCross contrast; nevertheless, this activation difference could be the effect of the same-patterned FEF activity. This activation exists in Green-Blue and Cross-Green comparisons and shows the differential processing of green pair, which is discriminated easier than the other two color pairs.

However, these brain responses are not a direct measure of task difficulty; in order to test the influence of difficulty level on performance and neural activation more directly, difficulty level should be manipulated within each category. Two pairs for a single categorical relationship can be defined in future experiments. For instance, brain activation in response to one green pair with two-unit distance to a midpoint such that there is a four-unit hue distance between them can be compared to the activation in response to another green pair with eight-unit distance to the same midpoint such that there is a sixteen-unit hue distance between them. This manipulation can yield a directly difficulty-related neural effect.

The present study was also aimed at exploring neural activation changes in response to separation of color pairs. The behavioral finding that color discrimination is easier when pairs were presented adjacently than when they were spatially separated draws attention to the importance of the spatial organization of display in which the stimuli were presented. The present results showed that the diameter of the display area and the visual angle between centers of stimuli, rather than presence or absence of a spatial gap between presented pairs, may be central to determine how well the pairs were discriminated. When the display dimensions suggested in Danilova and Mollon (2006) was provided, performance increased; but when the suggested levels were exceeded, performance decreased.

However, in order to test the inference that the spatial organization of the display area, such as the diameter of the display and distance between centers of stimuli, plays a central role in determining performance and neural responses, rather than spatial separation more directly, future experiments should manipulate both separation and spatial organization (e.g. radius, center distances, etc.)

The decline in performance in separated trials was found to be associated with greater brain activation in attention-related areas (Cuneus and Lingual Gyrus). This can be inferred as an increase in cognitive load caused by moving the centers of color pairs away from each other and expanding the width of the area occupied by the stimuli.

Briefly, the present study suggests two main ideas: first, there is a systematic performance decline throughout the green-blue region, which is also evident in difficulty-related signal changes in the brain, and second, the spatial separation of color stimuli caused a decrease in performance and produced attention-related neural responses. To the best of our knowledge, our study is the first study to challenge the long existing view of categorical color perception through the use of functional magnetic resonance imaging.

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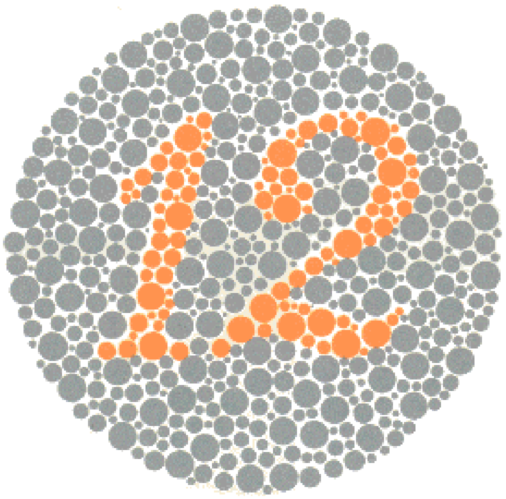
APPENDIX A

ISHIHARA COLOR BLINDNESS TEST

Ishihara Plate No:1



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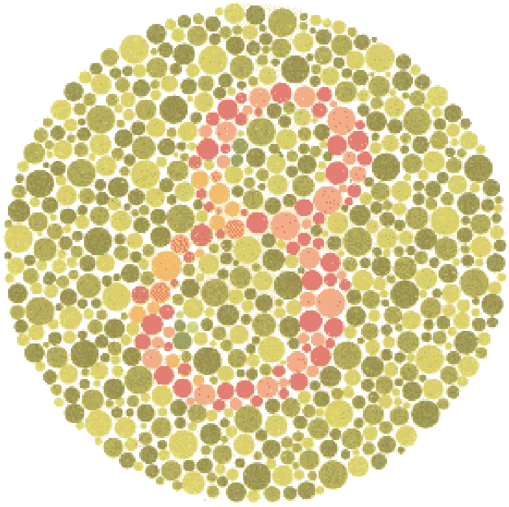

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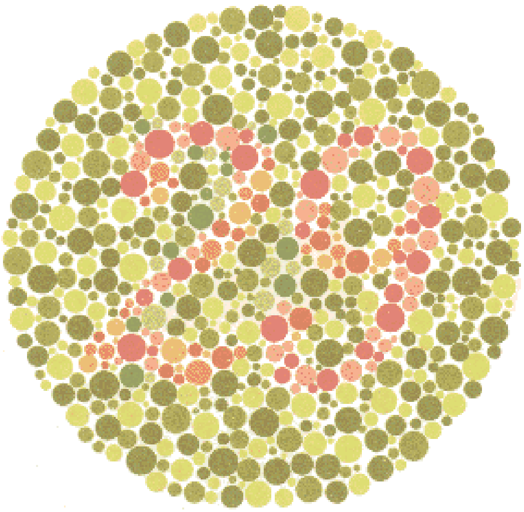

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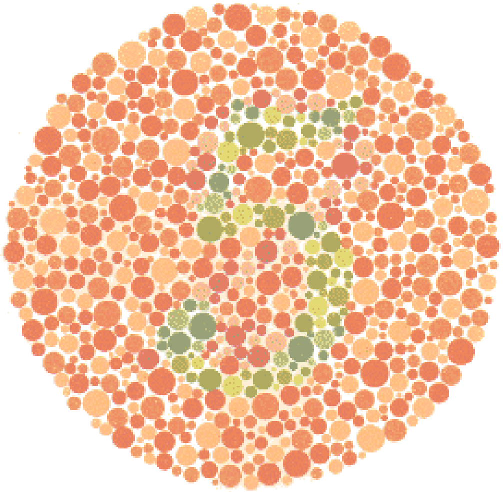

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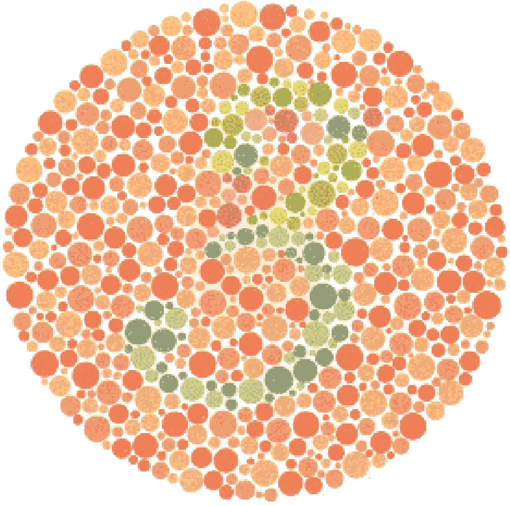

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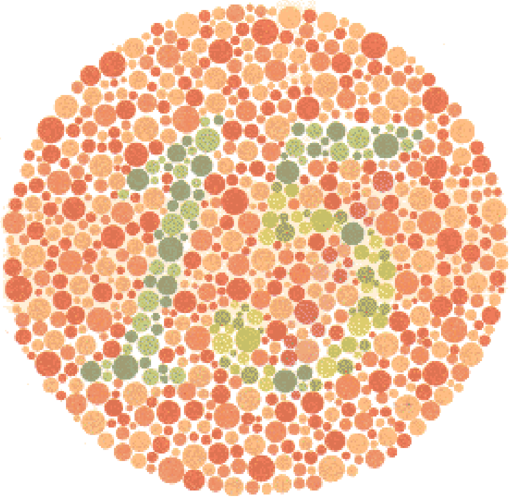

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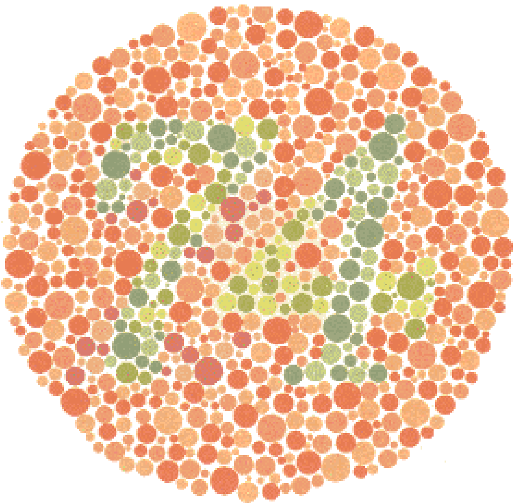
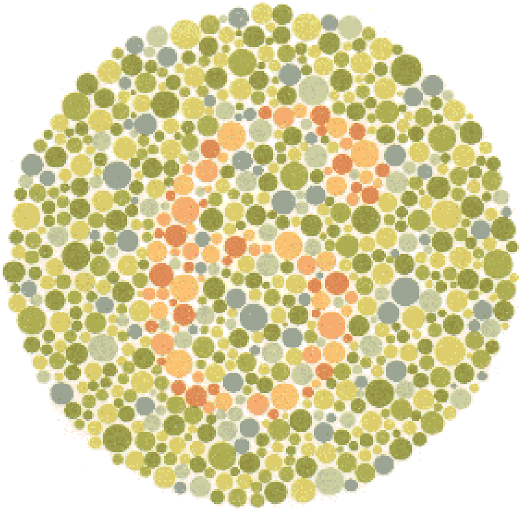
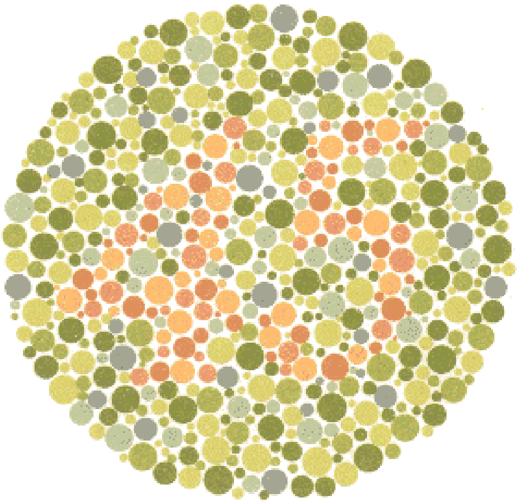


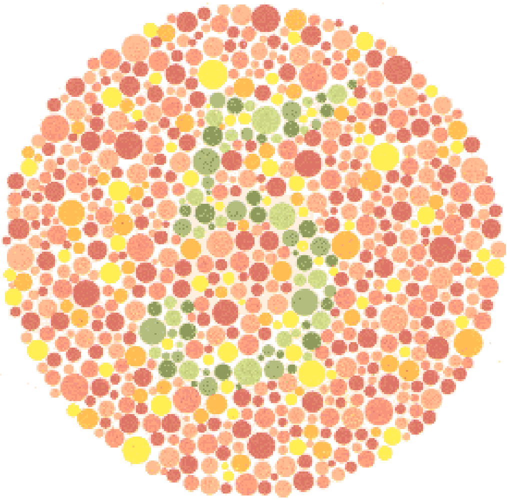
Ishihara Plate No:8



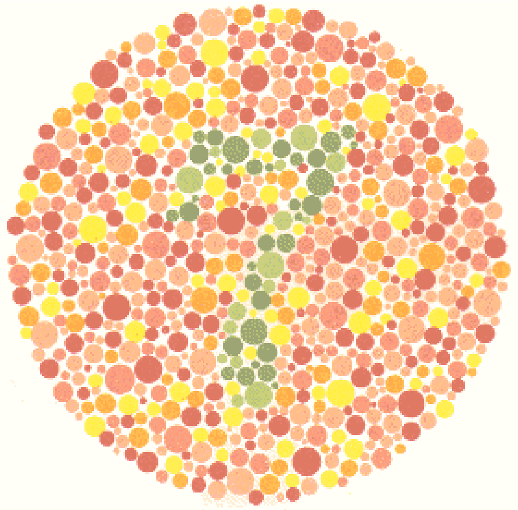
Ishihara Plate No:9



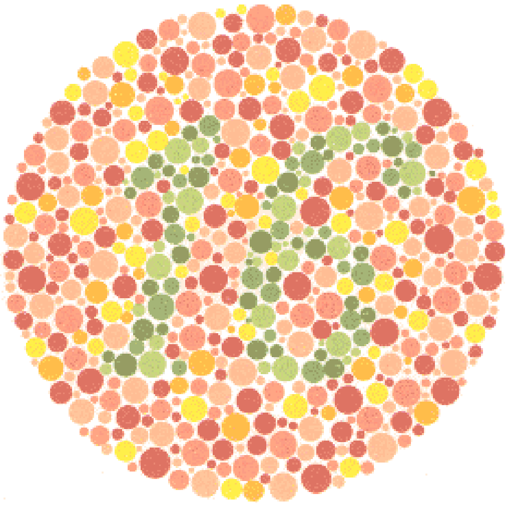
Ishihara Plate No:10



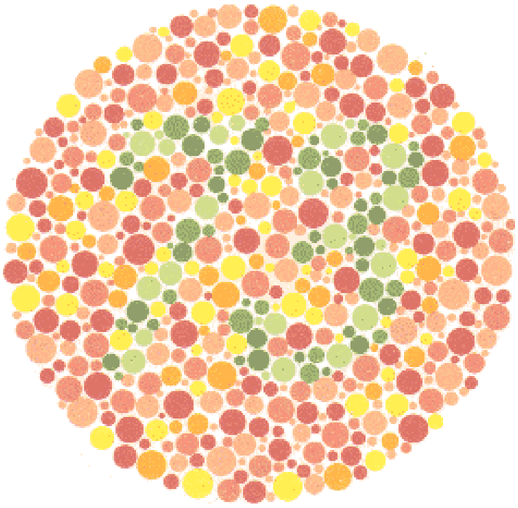
Ishihara Plate No:11



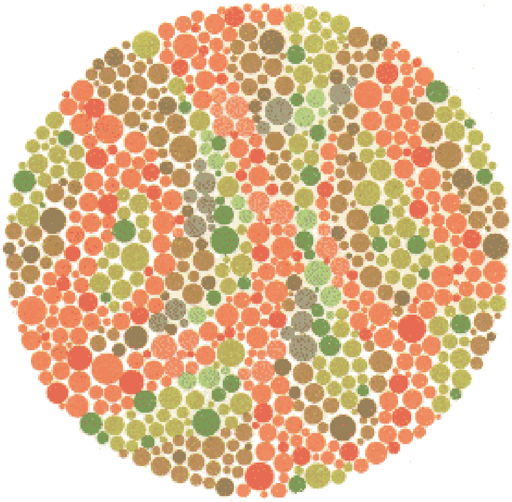
Ishihara Plate No:12



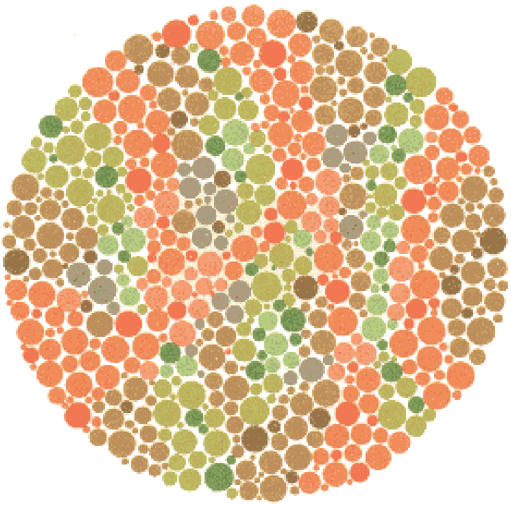
Ishihara Plate No:13



Ishihara Plate No:14



Ishihara Plate No:15



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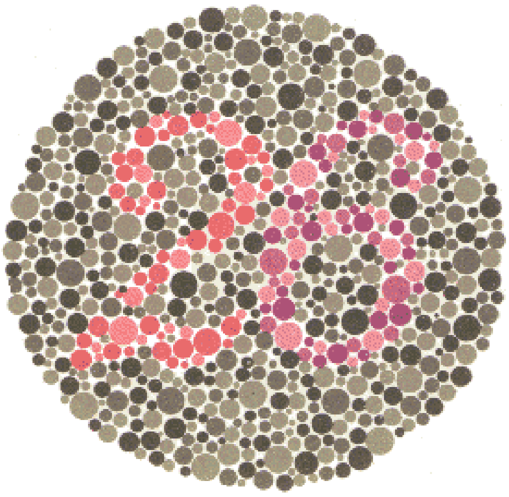

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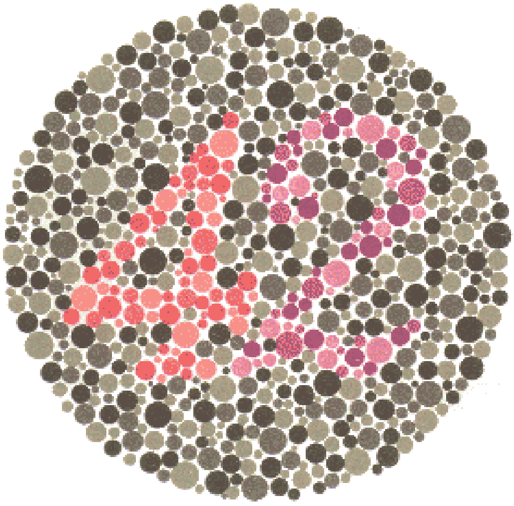

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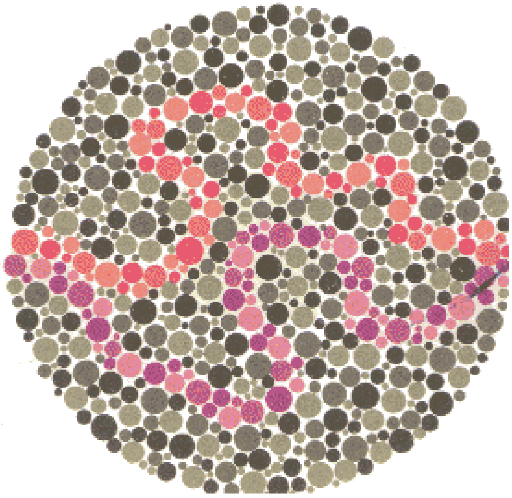
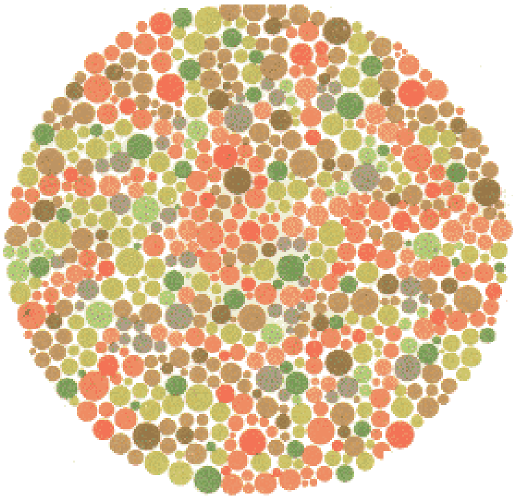
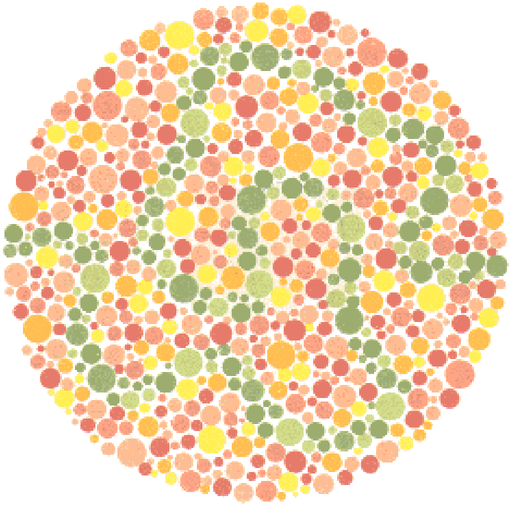


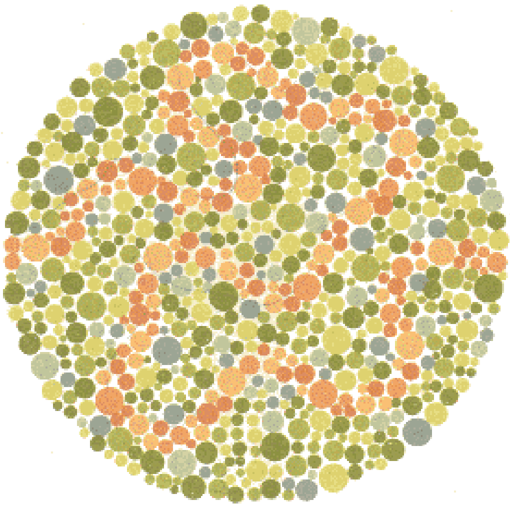
Ishihara Plate No:19



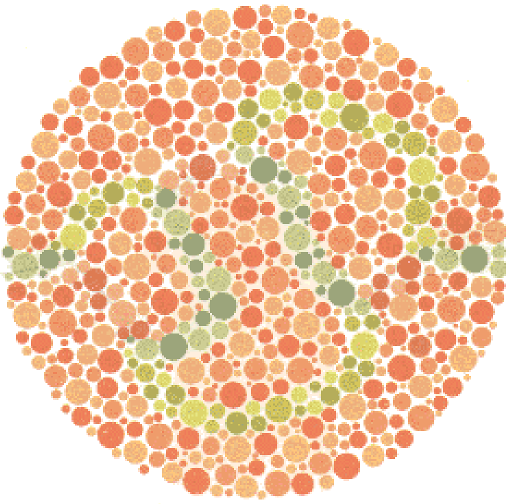
Ishihara Plate No:20



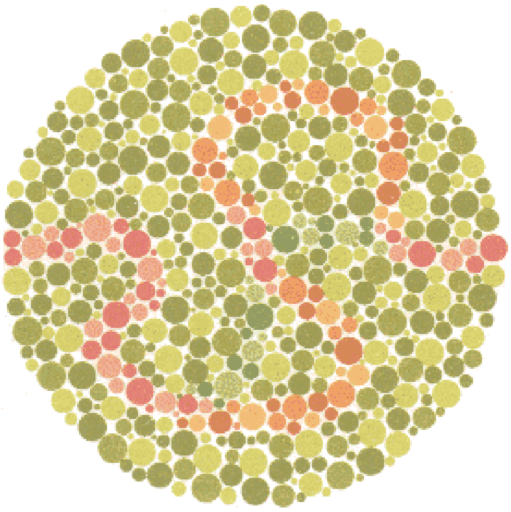
Ishihara Plate No:21



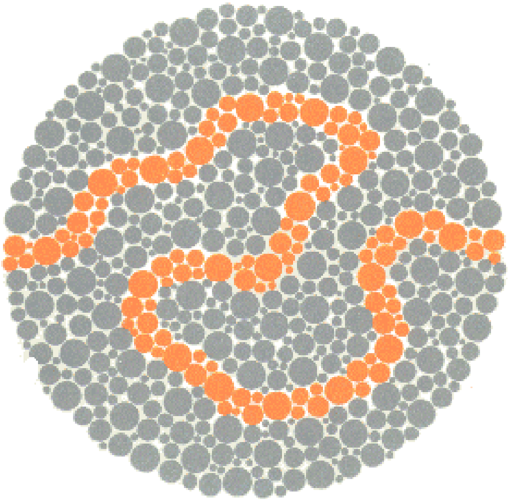
Ishihara Plate No:22



Ishihara Plate No:23



Ishihara Plate No:24



APPENDIX B

BILGILENDIRILMIS GONULLU OLUR FORMU

Araştırmanın adı: Renk Algısı Üzerindeki Kategorik Etkinin Fonksiyonel Manyetik Rezonans Görüntüleme Yöntemi ile İncelenmesi
Sorumlu araştırmacı: Yard. Doç. Dr. Didem Gökçay
Araştırmanın yapılacağı yer: ODTÜ Enformatik Enstitüsü, Bilkent UMRAM MR Merkezi

Orta Doğu Teknik Üniversitesi Enformatik Enstitüsü Bilişsel Bilimler bölümü yüksek lisans öğrencisi Şeyma Koç tarafından, yine Orta doğu Teknik Üniversitesi Enformatik Enstitüsü Öğretim Üyelerinden Yrd. Doç. Dr. Didem Gökçay'ın danışmanlığında ve Bilkent Üniversitesi Psikoloji Bölümü Başkanı Doç. Dr. Emre Özgen'in ortak danışmanlığında, yüksek lisans tezi kapsamında, renk ayrımı sırasında ortaya çıkan beyin aktivitesini değerlendirmek için planlanan bu araştırma projesine katılmak için davet edilmektesiniz. Çalışma sadece sağlıklı yetişkinleri kapsamaktadır ve çalışmaya 20 gönüllü katılacaktır.

Beyin görüntülemesi UMRAM MR Merkezi'nde bulunan ve beyin kan akımını ölçmeye yarayan MR cihazı yardımıyla yapılacaktır ve herhangi bir potansiyel risk içermemektedir. MR cihazında bilindiği üzere, herhangi bir radyoaktif madde ya da X-ışını kullanılmaz, klinik olarak günlük hayatımızda pek çok uygulamaları vardır.

Katılımcılardan yatar pozisyonda başlarına bir aygıt giydirilerek, MR içerisindeki aynaya yansıtılan görsellere yanıt vermeleri istenmektedir. Deneyde MR cihazı içerisinde gözünüzün yaklaşık 15 cm uzağına bir ayna düzeneği yerleştirilecektir. Bu düzenek sayesinde ekrandan yansıtılan renkleri görebilecek ve değerlendirebileceksiniz. Ekranda birbirine bitişik dikdörtgen şeklinde ya da birbirinden ayrık kare şeklinde renkler gösterilecektir. Renkler bitişik dikdörtgen şeklinde gösterildiğinde dikdörtgenin en sağ ya da en sol kısmı bir renkten, geri kalan kısımları başka bir renkten oluşacak; renkler ayrık kareler şeklinde gösterildiğinde ise en sağ ya da en sol kare bir renkten, geri kalan kareler başka bir renkten oluşacaktır. Sizden, hangi taraftaki rengin farklı olduğu kararınıza göre cevap düğmelerine basmanız istenecektir.

Bu uygulama yaklaşık olarak 30dk sürecek olup, size herhangi bir fiziksel zarar vermeyecektir. MR çekimi, uygun önlemler alındığı takdirde zararsız bir işlemdir. Ancak hamile olan ya da kapalı yer korkusu olan kişilerin MR cihazına girmesi sakıncalıdır. Bununla birlikte, metal maddelerin MR cihazındaki yüksek güçteki mıknatıstan etkilenmesi ve görüntü kalitesini düşürmesi sebebiyle vücudunda metal protez, kalp pili ve diş teli gibi cihazlar bulunan kişiler çalışmaya katılamazlar. MR çekimi başladığında ritmik sesler duyacaksınız. Personel bu sesi azaltmak için size kulak tıkacı temin edecektir. Cihazın içerisinde, iletişim yapabilmeniz için yerleştirilmiş bir ses sistemi bulunmaktadır. Bu vesileyle teknisyen ile konuşmanız mümkündür. Çekim süresince hiçbir kafa hareketi olmaması gerekmektedir. Öksürme, boğazı temizleyecek şekilde yutkunma gibi hareketler çekim kalitesini düşürdüğünden, bazı çekimlerin tekrarlanması gerekebilir. Bu nedenle mümkün olduğunca kafanızı kıpırdatmamanız gerekmektedir.

Bu çalışmada hakkınızda edinilen tüm bilgiler gizli tutulacak ve sadece araştırmacıların bilgisine sunulacaktır. Bu çalışmadan herhangi bir rapor veya yayın yapılması halinde okuyucuların sizleri tanımasına yol açacak hiçbir kişisel bilgi bulunmayacaktır.

Deney, genel olarak kişisel rahatsızlık verecek unsurlar içermemektedir. Ancak, katılım sırasında herhangi bir nedenden ötürü kendinizi rahatsız hissederseniz yanınızda duracak mikrofona sesli komut vererek deneyi yarıda bırakıp çıkmakta serbestsiniz. Araştırmaya katılımınız tamamıyla gönüllülük çerçevesinde olup, istediğiniz zaman, hiçbir yaptırım veya cezaya maruz kalmadan, hiçbir hak kaybetmeksizin araştırmaya katılmayı reddedebilir veya araştırmadan çekilebilirsiniz. Çalışmaya katılmamayı da seçebilirsiniz.

Deney sonunda, bu çalışmayla ilgili sorularınız cevaplanacaktır. Bu çalışmaya katıldığınız için şimdiden teşekkür ederiz. Çalışma hakkında daha fazla bilgi almak için veya herhangi bir sorunuz olduğunda, ODTÜ Enformatik Enstitüsü Bilişsel Bilimler Bölümü yüksek lisans öğrencisi Şeyma Koç (Tel: 05058071086, E-posta: seymakocpsyc@gmail.com), ODTÜ Enformatik Enstitüsü Öğretim Üyesi Yrd. Doç. Dr. Didem Gökçay (Oda: A-216, Tel: 03122103750, E-posta: didemgokcay@ii.metu.edu.tr) ya da Bilkent Üniversitesi Psikoloji Bölümü Başkanı Doç. Dr. Emre Özgen (Oda: A-354, Tel: 03122903415, E-posta:e ozgen@bilkent.edu.tr) ile iletişim kurabilirsiniz.

Bilgilendirilmiş Gönüllü Olur Formu'ndaki tüm açıklamaları okudum. Yukarıda konusu ve amacı belirtilen araştırma ile ilgili tüm yazılı ve sözlü açıklama aşağıda adı belirtilen araştırmacı tarafından yapıldı. Bu çalışmaya tamamen gönüllü olarak katılıyorum ve istediğim zaman gerekçeli veya gerekçesiz olarak yarıda kesip çıkabileceğimi veya kendi isteğime bakılmaksızın araştırmacı tarafından araştırma dışı bırakılabileceğimi biliyorum. Verdiğim bilgilerin bilimsel amaçlı yayınlarda isim bilgilerim olmadan kullanılmasını, görüntü kayıtlarıma sadece araştırmacı veya etik kurul tarafından gizli tutulmak kaydıyla erişilebilmesini kabul ediyorum. Kendi özgür iredemle, hiçbir baskı ve zorlama olmadan "Renk Algısı Üzerindeki Kategorik Etkinin Fonksiyonel Manyetik Rezonans Görüntüleme Yöntemi İle İncelenmesi" adlı çalışmaya katılmayı kabul ettiğimi ve bu formun bir kopyasının bana verildiğini aşağıdaki imzamla beyan ederim.

Gönüllü:

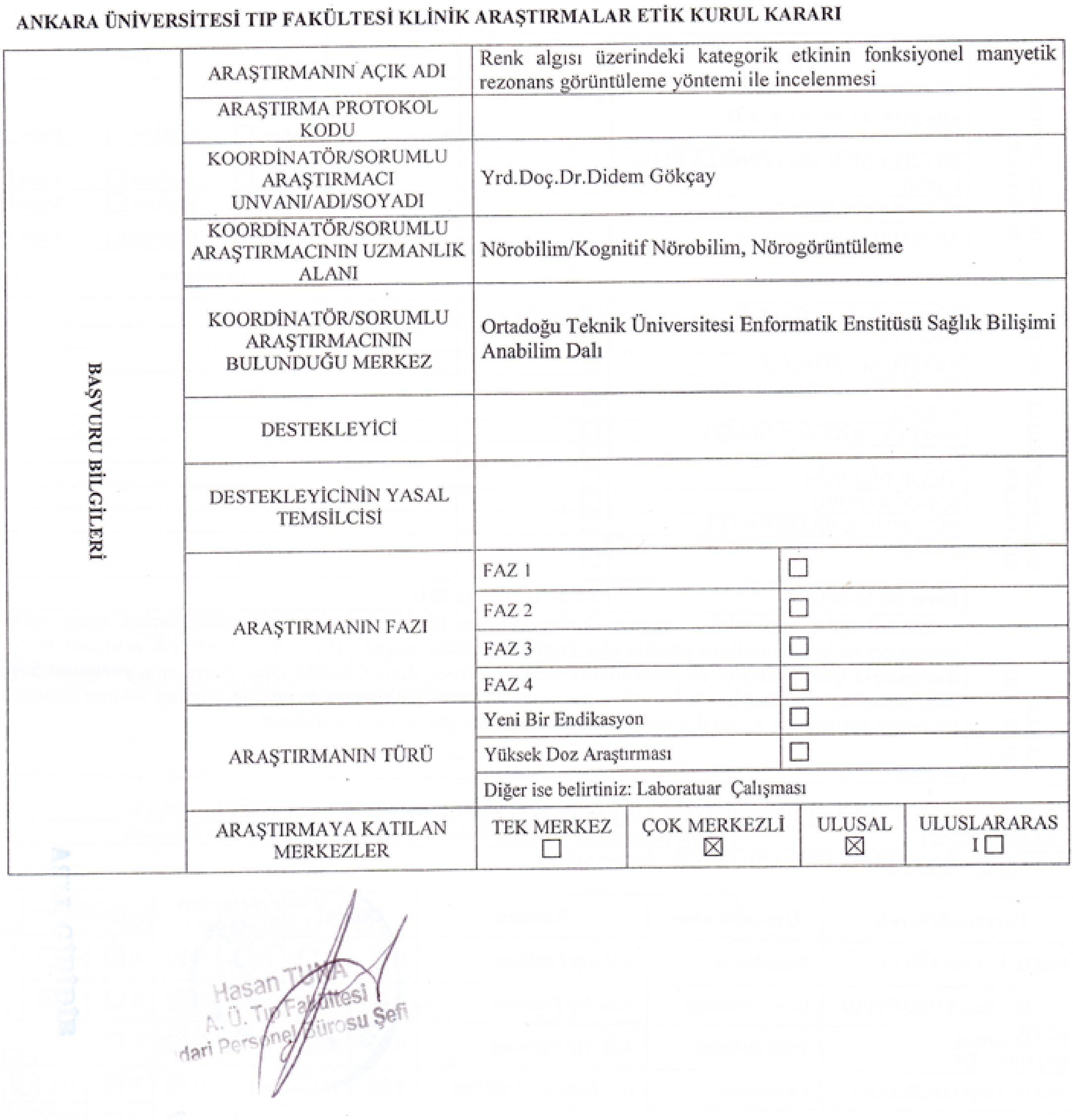
Adı Soyadı:	Tarih —/—/—	İmza
Adres ve telefon:		

Tanıklık Eden Yardımcı Araştırmacı:

Adı Soyadı:	Tarih —/—/—	İmza

APPENDIX C

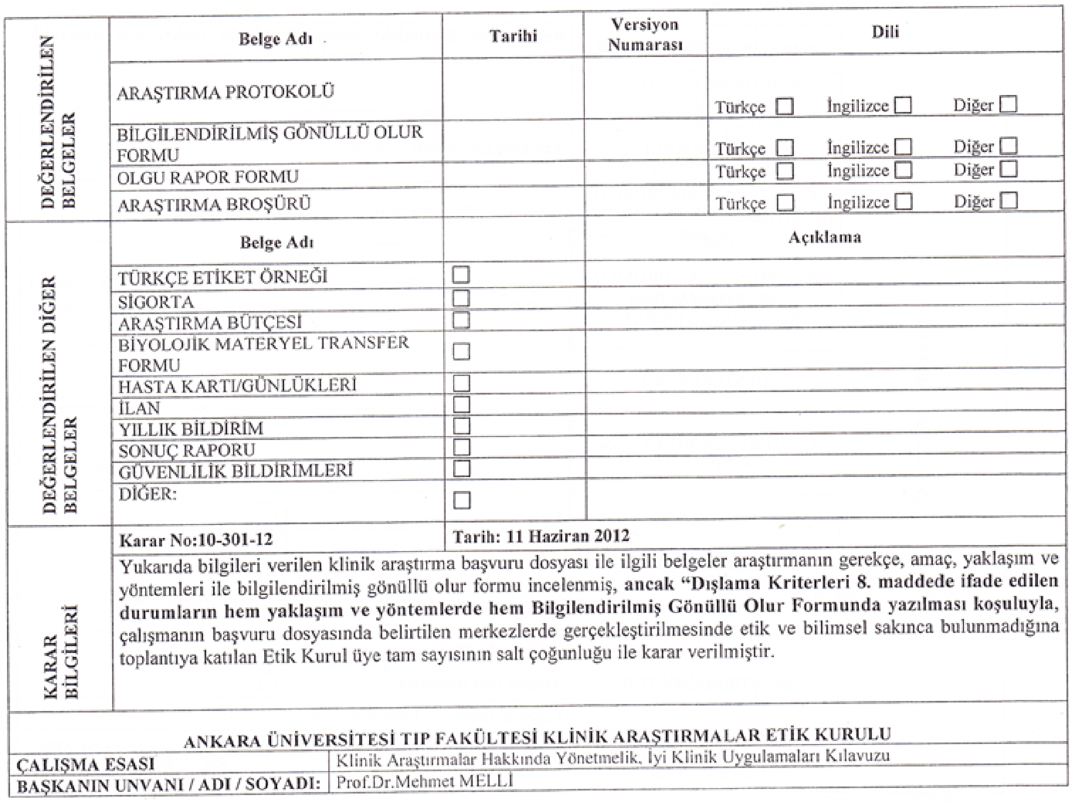
ETHICAL APPROVAL



ANKARA ÜNİVERSİTESİ TIP FAKÜLTESİ KLİNİK ARAŞTIRMALAR ETİK KURUL KARARI

BAŞVURU BİLGİLERİ	ARAŞTIRMANIN AÇIK ADI	Renk algısı üzerindeki kategorik etkinin fonksiyonel manyetik rezonans görüntüleme yöntemi ile incelenmesi			
	ARAŞTIRMA PROTOKOL KODU				
	KOORDİNATÖR/SORUMLU ARAŞTIRMACI UNVANI/ADI/SOYADI	Yrd.Doç.Dr.Didem Gökçay			
	KOORDİNATÖR/SORUMLU ARAŞTIRMACININ UZMANLIK ALANI	Nörobilim/Kognitif Nörobilim, Nörogörüntüleme			
	KOORDİNATÖR/SORUMLU ARAŞTIRMACININ BULUNDUĞU MERKEZ	Ortadoğu Teknik Üniversitesi Enformatik Enstitüsü Sağlık Bilişimi Anabilim Dalı			
	DESTEKLEYİCİ				
	DESTEKLEYİCİNİN YASAL TEMSİLCİSİ				
	ARAŞTIRMANIN FAZI	FAZ 1	☐		
		FAZ 2	☐		
		FAZ 3	☐		
		FAZ 4	☐		
	ARAŞTIRMANIN TÜRÜ	Yeni Bir Endikasyon	☐		
		Yüksek Doz Araştırması	☐		
		Diğer ise belirtiniz: Laboratuar Çalışması			
	ARAŞTIRMAYA KATILAN MERKEZLER	TEK MERKEZ ☐	ÇOK MERKEZLİ ☒	ULUSAL ☒	ULUSLARARASI ☐

Hasan TUNA
A. Ü. Tıp Fakültesi
dari Personel Bürosu Şefi



	Belge Adı	Tarihi	Versiyon Numarası	Dili
DEĞERLENDİRİLEN BELGELER	ARAŞTIRMA PROTOKOLÜ			Türkçe ☐ İngilizce ☐ Diğer ☐
	BİLGİLENDİRİLMİŞ GÖNÜLLÜ OLUR FORMU			Türkçe ☐ İngilizce ☐ Diğer ☐
	OLGU RAPOR FORMU			Türkçe ☐ İngilizce ☐ Diğer ☐
	ARAŞTIRMA BROŞÜRÜ			Türkçe ☐ İngilizce ☐ Diğer ☐

	Belge Adı		Açıklama
DEĞERLENDİRİLEN DİĞER BELGELER	TÜRKÇE ETİKET ÖRNEĞİ	☐	
	SİGORTA	☐	
	ARAŞTIRMA BÜTÇESİ	☐	
	BİYOLOJİK MATERYEL TRANSFER FORMU	☐	
	HASTA KARTI/GÜNLÜKLERİ	☐	
	İLAN	☐	
	YILLIK BİLDİRİM	☐	
	SONUÇ RAPORU	☐	
	GÜVENLİLİK BİLDİRİMLERİ	☐	
	DİĞER:	☐	

KARAR BİLGİLERİ	**Karar No:10-301-12**	**Tarih: 11 Haziran 2012**
	Yukarıda bilgileri verilen klinik araştırma başvuru dosyası ile ilgili belgeler araştırmanın gerekçe, amaç, yaklaşım ve yöntemleri ile bilgilendirilmiş gönüllü olur formu incelenmiş, **ancak "Dışlama Kriterleri 8. maddede ifade edilen durumların hem yaklaşım ve yöntemlerde hem Bilgilendirilmiş Gönüllü Olur Formunda yazılması koşuluyla,** çalışmanın başvuru dosyasında belirtilen merkezlerde gerçekleştirilmesinde etik ve bilimsel sakınca bulunmadığına toplantıya katılan Etik Kurul üye tam sayısının salt çoğunluğu ile karar verilmiştir.	

ANKARA ÜNİVERSİTESİ TIP FAKÜLTESİ KLİNİK ARAŞTIRMALAR ETİK KURULU

ÇALIŞMA ESASI	Klinik Araştırmalar Hakkında Yönetmelik, İyi Klinik Uygulamaları Kılavuzu
BAŞKANIN UNVANI / ADI / SOYADI:	Prof.Dr.Mehmet MELLİ

APPENDIX D

SAMPLE AFNI SCRIPTS

SUBJECT ♯5 preprocessing commands for all three runs:

```
to3d -time:zt 28 159 2000 altplus -prefix cps5_run1 *
```

```
3dToutcount -automask cps5_run1+orig >cps5_run1_headmotion.1D
1dplot cps5_run1_headmotion.1D
```

```
3dTshift -tzero 0 -heptic -prefix cps5_run1_tshift cps5_run1+orig
```

```
3dToutcount -automask cps5_run1_tshift+orig >cps5_run1_ headmotion_afterTshift.1D
1dplot cps5_run1_headmotion_afterTshift.1D
```

```
3dAllineate -base cps5_anat+orig -source cps5_run1_tshift+orig'[45]'
```

```
3dvolreg -base cps5_run1_tshift+orig'[45]' -prefix cps5_ run1_tshift_volreg -1Dfile
cps5_run1_motionfile.1D cps5_run1_tshift+orig'[0..158]'
1dplot cps5_run1_motionfile.1D
```

```
3dToutcount -automask cps5_run1_tshift_volreg+orig >cps5_run1_headmotion_ after-
Correction.1D 1dplot cps5_run1_headmotion_afterCorrection.1D
```

```
NUDGE plugin (cps5_run1_tshift_volreg_to_cps5_anat)
```

```
3dmerge -1blur_fwhm 6 -doall -prefix cps5_run1_tshift_volreg_merge cps5_run1_
tshift_volreg+orig
```

```
3dAutomask -prefix mask_cps5_run1_tshift_volreg_merge cps5_run1_tshift_
volreg_merge+orig
```

```
3dTstat -prefix mean_cps5_run1_tshift_volreg_merge
cps5_run1_tshift_volreg_merge+orig

3dcalc -a cps5_run1_tshift_volreg_merge+orig -b
mean_cps5_run1_tshift_volreg_merge+orig -c
mask_cps5_run1_tshift_volreg_merge+orig -expr "(a/b*100)*c" -prefix
cps5_run1_preprocessed
```

```
to3d -time:zt 28 156 2000 altplus -prefix cps5_run2 *

3dToutcount -automask cps5_run2+orig > cps5_run2_headmotion.1D
1dplot cps5_run2_headmotion.1D

3dTshift -tzero 0 -heptic -prefix cps5_run2_tshift cps5_run2+orig

3dToutcount -automask cps5_run2_tshift+orig > cps5_run2_headmotion_afterTshift.1D
1dplot cps5_run2_headmotion_afterTshift.1D

3dAllineate -base cps5_anat+orig -source cps5_run2_tshift+orig'[100]'

3dvolreg -base cps5_run2_tshift+orig'[100]' -prefix cps5_run2_tshift_volreg -1Dfile
cps5_run2_motionfile.1D cps5_run2_tshift+orig'[0..155]'
1dplot cps5_run2_motionfile.1D

3dToutcount -automask cps5_run2_tshift_volreg+orig >
cps5_run2_headmotion_afterCorrection.1D
1dplot cps5_run2_headmotion_afterCorrection.1D
```

NUDGE plugin (cps5_run2_tshift_volreg_to_cps4_run1_preprocessed & checked on cps5_anat)

```
3dmerge -1blur_fwhm 6 -doall -prefix cps5_run2_tshift_volreg_merge
cps5_run2_tshift_volreg+orig

3dAutomask -prefix mask_cps5_run2_tshift_volreg_merge
cps5_run2_tshift_volreg_merge+orig

3dTstat -prefix mean_cps5_run2_tshift_volreg_merge
cps5_run2_tshift_volreg_merge+orig

3dcalc -a cps5_run2_tshift_volreg_merge+orig -b
mean_cps5_run2_tshift_volreg_merge+orig -c
mask_cps5_run2_tshift_volreg_merge+orig -expr "(a/b*100)*c" -prefix
cps5_run2_preprocessed
```

```
to3d -time:zt 28 160 2000 altplus -prefix cps5_run3 *
```

```
3dToutcount -automask cps5_run3+orig > cps5_run3_headmotion.1D
1dplot cps5_run3_headmotion.1D
```

```
3dTshift -tzero 0 -heptic -prefix cps5_run3_tshift cps5_run3+orig
```

```
3dToutcount -automask cps5_run3_tshift+orig > cps5_run3_headmotion_afterTshift.1D
1dplot cps5_run3_headmotion_afterTshift.1D
```

```
3dAllineate -base cps5_anat+orig -source cps5_run3_tshift+orig'[45]'
```

```
3dvolreg -base cps5_run3_tshift+orig'[50]' -prefix cps5_run3_tshift_volreg -1Dfile
cps5_run3_motionfile.1D cps5_run3_tshift+orig'[0..159]'
1dplot cps5_run3_motionfile.1D
```

```
3dToutcount -automask cps5_run3_tshift_volreg+orig >
cps5_run3_headmotion_afterCorrection.1D
1dplot cps5_run3_headmotion_afterCorrection.1D
```

NUDGE plugin (cps5_run3_tshift_volreg_to_cps5_run1_preprocessed & checked on cps5_anat)

```
3dmerge -1blur_fwhm 6 -doall -prefix cps5_run3_tshift_volreg_merge
cps5_run3_tshift_volreg+orig
```

```
3dAutomask -prefix mask_cps5_run3_tshift_volreg_merge
cps5_run3_tshift_volreg_merge+orig
```

```
3dTstat -prefix mean_cps5_run3_tshift_volreg_merge
cps5_run3_tshift_volreg_merge+orig
```

```
3dcalc -a cps5_run3_tshift_volreg_merge+orig -b
mean_cps5_run3_tshift_volreg_merge+orig -c
mask_cps5_run3_tshift_volreg_merge+orig -expr "(a/b*100)*c" -prefix
cps5_run3_preprocessed
```

NUDGE plugin (preprocessed runs checked on each other & checked on cps5_anat)

Concatenation of all preprocessed runs:

```
3dTcat -prefix cps5_allruns cps5_run1_preprocessed+orig'[0..158]'
cps5_run2_preprocessed+orig'[0..155]' cps5_run3_preprocessed+orig'[0..159]'
```

SUBJECT #5 deconvolution command:
(the command is rearranged for easier track)

```
3dDeconvolve -polort 3 -input cps5_allruns+orig -concat 3runindexes.txt

-num_stimts 3
-stim_file 1 "cps5_smooth_waveform_within_green.1D" -stim_label 1 green
-stim_file 2 "cps5_smooth_waveform_cross_category.1D" -stim_label 2 cross
-stim_file 3 "cps5_smooth_waveform_within_blue.1D" -stim_label 3 blue

-num_glt 3
-gltsym "SYM: green -cross" -glt_label 1 greenVScross
-gltsym "SYM: blue -cross" -glt_label 2 blueVScross
-gltsym "SYM: green -blue" -glt_label 3 greenVSblue

-tout -fout -bucket cps5_category_stats -fitts cps5_category_fitts -xjpeg
cps5_category_xmat.jpg -x1D cps5_category_xmat.1D
```

Calculation of the Average Brain:
(the command is rearranged for easier track)

```
3dcalc

-a cps1_anat_deobliqued+tlrc
-b cps2_anat_deobliqued+tlrc
-c cps3_anat_deobliqued+tlrc
-d cps4_anat_deobliqued+tlrc
-e cps5_anat+tlrc
-f cps6_anat_deobliqued+tlrc
-g cps7_anat_deobliqued+tlrc
-h cps8_anat+tlrc
-i cps9_anat_deobliqued+tlrc
-j cps10_anat_deobliqued+tlrc
-k cps11_anat_deobliqued+tlrc
-l cps12_anat_deobliqued+tlrc
-m cps13_anat_deobliqued+tlrc
-n cps14_anat+tlrc
-p cps15_anat_deobliqued+tlrc
-r cps16_anat_deobliqued+tlrc
-s cps17_anat+tlrc
-t cps18_anat_deobliqued+tlrc
-v cps19_anat+tlrc
-y cps20_anat_deobliqued+tlrc

-expr "(a+b+c+d+e+f+g+h+i+j+k+l+m+n+p+r+s+t+v+y)/20"

-prefix mean_anatomical
```

Group Analysis: ANOVA command for category varible with three levels: (the command is rearranged for easier track)

```
3dANOVA -DAFNI_FLOATIZE=YES

-levels 3

-dset 1 cps1_category_stats_warped+tlrc[1]
-dset 1 cps2_category_stats_warped+tlrc[1]
-dset 1 cps3_category_stats_warped+tlrc[1]
-dset 1 cps4_category_stats_warped+tlrc[1]
-dset 1 cps5_category_stats+tlrc[1]
-dset 1 cps6_category_stats_warped+tlrc[1]
-dset 1 cps7_category_stats_warped+tlrc[1]
-dset 1 cps8_category_stats+tlrc[1]
-dset 1 cps9_category_stats_warped+tlrc[1]
-dset 1 cps10_category_stats_warped+tlrc[1]
-dset 1 cps11_category_stats_warped+tlrc[1]
-dset 1 cps12_category_stats_warped+tlrc[1]
-dset 1 cps13_category_stats_warped+tlrc[1]
-dset 1 cps14_category_stats+tlrc[1]
-dset 1 cps15_category_stats_warped+tlrc[1]
-dset 1 cps16_category_stats_warped+tlrc[1]
-dset 1 cps17_category_stats+tlrc[1]
-dset 1 cps18_category_stats_warped+tlrc[1]
-dset 1 cps19_category_stats+tlrc[1]
-dset 1 cps20_category_stats_warped+tlrc[1]

-dset 2 cps1_category_stats_warped+tlrc[7]
-dset 2 cps2_category_stats_warped+tlrc[7]
-dset 2 cps3_category_stats_warped+tlrc[7]
-dset 2 cps4_category_stats_warped+tlrc[7]
-dset 2 cps5_category_stats+tlrc[7]
-dset 2 cps6_category_stats_warped+tlrc[7]
-dset 2 cps7_category_stats_warped+tlrc[7]
-dset 2 cps8_category_stats+tlrc[7]
-dset 2 cps9_category_stats_warped+tlrc[7]
-dset 2 cps10_category_stats_warped+tlrc[7]
-dset 2 cps11_category_stats_warped+tlrc[7]
-dset 2 cps12_category_stats_warped+tlrc[7]
-dset 2 cps13_category_stats_warped+tlrc[7]
-dset 2 cps14_category_stats+tlrc[7]
-dset 2 cps15_category_stats_warped+tlrc[7]
-dset 2 cps16_category_stats_warped+tlrc[7]
-dset 2 cps17_category_stats+tlrc[7]
-dset 2 cps18_category_stats_warped+tlrc[7]
-dset 2 cps19_category_stats+tlrc[7]
-dset 2 cps20_category_stats_warped+tlrc[7]
```

```
-dset 3 cps1_category_stats_warped+tlrc[4]
-dset 3 cps2_category_stats_warped+tlrc[4]
-dset 3 cps3_category_stats_warped+tlrc[4]
-dset 3 cps4_category_stats_warped+tlrc[4]
-dset 3 cps5_category_stats+tlrc[4]
-dset 3 cps6_category_stats_warped+tlrc[4]
-dset 3 cps7_category_stats_warped+tlrc[4]
-dset 3 cps8_category_stats+tlrc[4]
-dset 3 cps9_category_stats_warped+tlrc[4]
-dset 3 cps10_category_stats_warped+tlrc[4]
-dset 3 cps11_category_stats_warped+tlrc[4]
-dset 3 cps12_category_stats_warped+tlrc[4]
-dset 3 cps13_category_stats_warped+tlrc[4]
-dset 3 cps14_category_stats+tlrc[4]
-dset 3 cps15_category_stats_warped+tlrc[4]
-dset 3 cps16_category_stats_warped+tlrc[4]
-dset 3 cps17_category_stats+tlrc[4]
-dset 3 cps18_category_stats_warped+tlrc[4]
-dset 3 cps19_category_stats+tlrc[4]
-dset 3 cps20_category_stats_warped+tlrc[4]

-ftr Color

-mean 1 Green
-mean 2 Blue
-mean 3 Cross

-diff 1 2 GvsB
-diff 2 3 BvsC
-diff 1 3 GvsC

-contr 1 -1 0 GreenvsBlue
-contr 0 1 -1  BluevsCross
-contr -1 0 1 CrossvsGreen

-contr 2 -1 -1 GvsBC
-contr -1 2 -1 BvsGC
-contr -1 -1 2 CvsGB

-bucket cp_anova_category
```

Group Analysis: ANOVA command for spatial display varible with three levels (the command is rearranged for easier track)

```
3dANOVA -DAFNI_FLOATIZE=YES

-levels 2

-dset 1 cps1_gap_stats_warped+tlrc[1]
-dset 1 cps2_gap_stats_warped+tlrc[1]
-dset 1 cps3_gap_stats_warped+tlrc[1]
-dset 1 cps4_gap_stats_warped+tlrc[1]
-dset 1 cps5_gap_stats+tlrc[1]
-dset 1 cps6_gap_stats_warped+tlrc[1]
-dset 1 cps7_gap_stats_warped+tlrc[1]
-dset 1 cps8_gap_stats+tlrc[1]
-dset 1 cps9_gap_stats_warped+tlrc[1]
-dset 1 cps10_gap_stats_warped+tlrc[1]
-dset 1 cps11_gap_stats_warped+tlrc[1]
-dset 1 cps12_gap_stats_warped+tlrc[1]
-dset 1 cps13_gap_stats_warped+tlrc[1]
-dset 1 cps14_gap_stats+tlrc[1]
-dset 1 cps15_gap_stats_warped+tlrc[1]
-dset 1 cps16_gap_stats_warped+tlrc[1]
-dset 1 cps17_gap_stats+tlrc[1]
-dset 1 cps18_gap_stats_warped+tlrc[1]
-dset 1 cps19_gap_stats+tlrc[1]
-dset 1 cps20_gap_stats_warped+tlrc[1]

-dset 2 cps1_gap_stats_warped+tlrc[4]
-dset 2 cps2_gap_stats_warped+tlrc[4]
-dset 2 cps3_gap_stats_warped+tlrc[4]
-dset 2 cps4_gap_stats_warped+tlrc[4]
-dset 2 cps5_gap_stats+tlrc[4]
-dset 2 cps6_gap_stats_warped+tlrc[4]
-dset 2 cps7_gap_stats_warped+tlrc[4]
-dset 2 cps8_gap_stats+tlrc[4]
-dset 2 cps9_gap_stats_warped+tlrc[4]
-dset 2 cps10_gap_stats_warped+tlrc[4]
-dset 2 cps11_gap_stats_warped+tlrc[4]
-dset 2 cps12_gap_stats_warped+tlrc[4]
-dset 2 cps13_gap_stats_warped+tlrc[4]
-dset 2 cps14_gap_stats+tlrc[4]
-dset 2 cps15_gap_stats_warped+tlrc[4]
-dset 2 cps16_gap_stats_warped+tlrc[4]
-dset 2 cps17_gap_stats+tlrc[4]
-dset 2 cps18_gap_stats_warped+tlrc[4]
-dset 2 cps19_gap_stats+tlrc[4]
-dset 2 cps20_gap_stats_warped+tlrc[4]
```

```
-ftr Gap

-mean 1 Adjacent
-mean 2 Separated

-diff 1 2 AvsS

-contr 1 -1 AdjvsSprt
-contr -1 1 SprtvsAdj

-bucket cp_anova_gap
```

METU
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YAZARIN

Soyadı : KOÇ
Adı : ŞEYMA
Bölümü : BİLİŞSEL BİLİMLER

TEZİN ADI : **CATEGORICAL EFFECT STUDIED THROUGH FMRI IN COLOR PERCEPTION**

TEZİN TÜRÜ : Yüksek Lisans ☒ Doktora ☐

1. Tezimin tamamı dünya çapında erişime açılsın ve kaynak gösterilmek şartıyla tezimin bir kısmı veya tamamının fotokopisi alınsın. ☐

2. Tezimin tamamı yalnızca Orta Doğu Teknik Üniversitesi kullanıcılarının erişimine açılsın. (Bu seçenekle tezinizin fotokopisi ya da elektronik kopyası Kütüphane aracılığı ile ODTÜ dışına dağıtılmayacaktır.) ☐

3. Tezim bir (1) yıl süreyle erişime kapalı olsun. (Bu seçenekle tezinizin fotokopisi ya da elektronik kopyası Kütüphane aracılığı ile ODTÜ dışına dağıtılmayacaktır.) ☒

Yazarın imzası   Tarih