EFFECTS OF COLOR AND COLORED LIGHT ON DEPTH PERCEPTION

A THESIS
SUBMITTED TO THE DEPARTMENT OF INTERIOR ARCHITECTURE AND ENVIRONMENTAL DESIGN AND THE INSTITUTE OF ECONOMICS AND SOCIAL SCIENCES OF BİLKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF FINE ARTS

By
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August, 2010

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

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ABSTRACT

EFFECTS OF COLOR AND COLORED LIGHT ON DEPTH PERCEPTION

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The main purpose of this study is to understand the relationship between different objects and background colors, and depth perception in interior spaces. The experiment was conducted in two phases which consist of colored background light pairs (cool white-orange, cool white-blue, cool white-green, cool white-red, warm white-cool white, red-green and orange-blue) with colored objects (orange, blue and gray) in front of them. A forced choice paired comparison method was used to evaluate the differences in depth perception caused by colors. The participants were students who were having their internships in Philips Research Eindhoven, Netherlands. Firstly, participants were tested for color blindness and visual acuity, and the ones who passed these tests participated in the experiment. After the first phase of the experiment, a second part was required in order to obtain more accurate results. The participants who had internally consistent results in the first phase participated in the second phase of the experiment. In both phases, participants judged the distances of two same colored objects in front of colored lit background by choosing the one which they perceived as closer to themselves. As a result, differences between hues are smaller than the variations in perception of the participants, so hue has a really small effect on depth perception when evaluated monocularly.

KEYWORDS: depth perception, color, colored lighting.

ÖZET

RENK VE RENKLİ IŞIĞIN DERİNLİK ALGISINA OLAN ETKİSİ

Deniz Atlı
İç Mimarlık ve Çevre Tasarımı Yüksek Lisans Programı
Danışman : Y. Doç. Dr. Nilgün Olguntürk
Temmuz, 2010

Bu çalısmanın amacı, renkli obje ve renkli arka fon ilişkisinin iç mekanda derinlik algısına olan etkilerini anlamak ve karşılaştırmaktır. Deney iki aşamalı olarak renkli fon ışığı çiftlerinin (soğuk beyaz-turuncu, soğuk beyaz-mavi, soğuk beyaz-yeşil, soğuk beyaz-kırmızı, sıcak beyaz-soğuk beyaz, kırmızı-yeşil ve turuncu-mavi) önünde renkli objelerle (turuncu, mavi ve gri) gerçekleştirilmiştir. Renklerin derinlik algısı üzerindeki etkilerini anlamak amacıyla karşılaştırmalı test uygulanmıştır. Katılımcılar, Philips Araştırma Merkezi, Eindhoven, Hollanda'da stajlarını sürdürmekte olan öğrencilerden oluşmaktadır. İlk olarak katılımcılara, renk körlüğü ve görme testleri verilmiştir. Bu testleri geçenler deneye katılmışlardır. Daha doğru sonuçlar elde etmek amacıyla, birinci bölümün ardından ikinci bir aşama daha deney yapılmıştır. Birinci aşamada kendi içerisinde tutarlı sonuçlara sahip olan katılımcılar, ikinci aşamada tekrar teste alınmıştır. Deneyin iki aşamasında da katılımcılar renkli ışık çiftleriyle aydınlatılmış fonun önünde iki tane, aynı renkli objenin uzaklıklarını kendilerine daha yakın olarak algıladıkları objeyi seçmek süretiyle değerlendirmişlerdir. Sonuç olarak, renk türleri arasındaki farklar katılımcılar arasındaki algı çeşitliliğinden daha küçüktür ve tek göz ile değerlendirildiğinde renk türünün derinlik algısı üzerinde çok az etkin bir faktör olduğu söylenebilir.

Anahtar kelimeler: derinlik algısı,renk, renkli aydınlatma.

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I want to dedicate this thesis to the memory of my invaluable instructor Cengiz Yener with respect for his guidance and support so that I would be involved in academic research area. Without his inspiration, I would not be able to start my academic studies on lighting design.

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1. INTRODUCTION

This thesis concerns color and examines its effects on depth perception as an influential factor of space perception. Perception is one of the main topics in a lot of research. It involves immediate and basic experiences of individuals, generated as stimuli, and it gives them meaning and organization (Matlin and Foley, 1997). One of the observed and experienced stimuli for individuals is the space which they live in. While experiencing that physical environment, there are two important physical factors: color and light, which start up the psychological process of perception. In that sense, the focus of this thesis is color and light effects on depth perception in interior spaces.

With the emerging technologies, there has been an increase in the use of color and colored light in both exterior and interior spaces. Especially with the LED technology, colored and more flexible uses in lighting design fulfill the expectation of individuals by creating desirable moods, atmospheres and identities of spaces. With different colors and color combinations of architectural objects and other equipments, different depth perception cues are obtained, and accordingly, different room size perceptions can be created. Therefore, it is important to understand the relations between color and colored light, and depth perception, which is the topic of many critical studies (Mount, Case, Sanderson and Brenner, 1956; Bailey, Grimm and Davoli, 2006; Ichihara, Kitagawa and Akutsu, 2007; Huang, 2007).

1.1. Aim of the Study

The main purpose of this study is to understand the relation between different objects and their background colors, and depth perception in interior spaces. In this manner, this study aims to understand if colored light has an effect on depth perception in interior spaces and how this can affect depth perception of colored objects.

It is important to understand colored light effects on depth perception because this may contribute to architectural design of interior spaces. Besides, the findings may be helpful not only architects but also lighting designers who have the ability to control the light.

1.2. Structure of the Thesis

The thesis consists of six chapters. The first chapter is the Introduction which gives some information about the topic that the study is going to cover. It gives a brief explanation of the importance of color, colored light and their relation with depth perception. The aim of the study and the structure of the thesis are also explained in this chapter.

The second chapter comprises some basic information on space perception and its relation with depth perception. Firstly, some definitions on the subject of perception are explored and an introduction to space perception is made. After that, the depth cues are categorized under two headings which are monocular and binocular cues, and the studies conducted on depth cues are explained. In the third chapter, basic terms of color and light which are important for this study are defined. In addition, how light and light color affect the appearance of colored surfaces is mentioned. Finally, the studies on both color and light effects on depth perception are reported.

In the fourth chapter, the aim, research questions and hypotheses of the study are described. The details about the methodology of the experiment are explained in categories, namely the sample group, description of the experiment room and stimuli, and the procedure that is conducted through the experiment. The data obtained is evaluated and the statistical method that is used in the analysis is explained. In the fifth chapter, the findings are discussed.

The sixth chapter is the Conclusion, which includes the major results of the study, states the primary outcome observed in the experiment and suggestions for further research topics.

2. THEORY OF SPACE PERCEPTION

There have been many definitions and categorizations for explaining the meaning of perception. It has been expressed as "[…] awareness of objects" by an individual in its simplest way (Ittelson, 1960, p. 4). In order to find out about the relation between individuals and their environment, the topic of perception has come into focus as a research topic for psychologists (Ittelson, 1960). In this manner, perception is explained as a two-way affair which involves incoming and outgoing channels. This two-way affair, covering the individual and his/her environment, is referred to as perceiving and acting, respectively. Besides, "[…] the function of perception is defined as to bring us into contact with the world outside of ourselves. It is usually stated that this contact is through our senses." (Ittelson, 1960, p. 9). According to this approach, the familiar five senses became a topic of research and as this study is on the appearance of color and light, it concerns visual perception.

2.1. Space Perception

The world in which an individual lives and sees is made up of three-dimensional structures, objects and spaces. As perception is one of the aspects that creates the relation between individual and his/her environment, this three-dimensionality and space are studied under the title of *space perception*. Besides, as perception drives through our senses, space perception is investigated under different categories such as, auditory or visual space perception. In order to understand how an individual experiences the three-dimensionality around himself/herself with the influence of color and light, this study focuses on *visual space perception*. Specifically, v*isual space perception* is defined as the ability to perceive the three-dimensional layout of our environment through visual experiences (Boff, Kaufman and Thomas, 1986). The three-dimensionality encloses the arrangement of individual particles, each in given size and location. The apparent location of each particle specifies its direction and distance from the point of view of the observing eye. In this manner, distance becomes one of the most important attributes of visual space perception. Since retinal image occurs two-dimensionally in our visual system, to perceive the distance of an object we need the third-dimension which is known as depth (Sekular and Blake, 1994). Retinal image uses two angles of line of sight which specify the position and the size. Besides these two angles, length of line of sight refers to the third dimension, that is depth (Steven, 1988). To observe distance, the knowledge of depth cues are studied. With the help of these depth cues, an individual can conduct three consecutive processes which are detection, discrimination and identification, to distinguishing objects from each other (Sekular and Blake, 1994).

2.1.1. Parameters of Depth Perception

Depth perception can be defined in two different ways as *absolute distance* and *relative distance*. The distance from an observer to an object is called *absolute distance*. If the object distance is considered according to the another, then it is called *relative distance*

(Matlin and Foley, 1983). Differentiation between these two definitions is important to name the spatial factor that affects an individuals' evaluation of distance. Besides, the location of an object relative to an observer is also defined as *egocentric direction,* which is descriptive information for the two-dimensional retinal image dependent on two angles of line of sight (Sekular and Blake, 1994).

As it is mentioned before, depth perception requires sources of information which are studied under the name of 'cues'. These cues are studied under two broad categories of monocular and binocular depth cues (Sekular and Blake, 1994). While remembering these cues, what the designer must be aware of is how these cues affect the perception of spatial depth and how they can be used to change the appearance of architectural space. Monocular depth cues are the ones that can be controlled by a designer more than the binocular ones when shaping architectural spaces. This is because monocular cues concern mostly the environmental factors, where binocular depth cues are the ones which are more physiological in spatial vision and which are affected by the environmental factors. Both monocular and binocular cues are the attributes that a designer should be aware of.

2.1.1.1. Monocular Depth Cues

Monocular depth cues, which are also known as *pictorial depth cues*, can be identified as *relative size, linear perspective, aerial perspective, interposition (occlusion), texture gradient, light and shade* and *color* (Michel, 1996; Bailey et. al, 2006; Sekular and

Blake, 1994; Cutting and Vishton, 1995; Sundet, 1978; Ittelson, 1960). Besides these, another cue that involves information provided by the eye muscles is *accommodation*. These cues of monocular depth perception are the ones that require no movement either from the object or the observer.

Accommodation in the eye occurs because of the change in the shape of the lens while focusing on objects at different distances. Thus, eye muscles respond differently towards the objects at different distances (Matlin and Foley, 1983). However, it has been mentioned in many sources that accommodation cue can function just for the distances that are immediately in front of you as it is also represented in Figure 2.1. (Cutting and Vishton, 1995). From the figure, it can be understood that after nearly 1 m, the effect of accommodation cue starts to decrease as it gets lower to the assumed utility threshold for information and after 10 m it has almost no effects. In some other sources, it was claimed that even for close ranges, “distance judgments based solely on accommodation are inaccurate” (Sekular and Blake, 1994, p. 218).

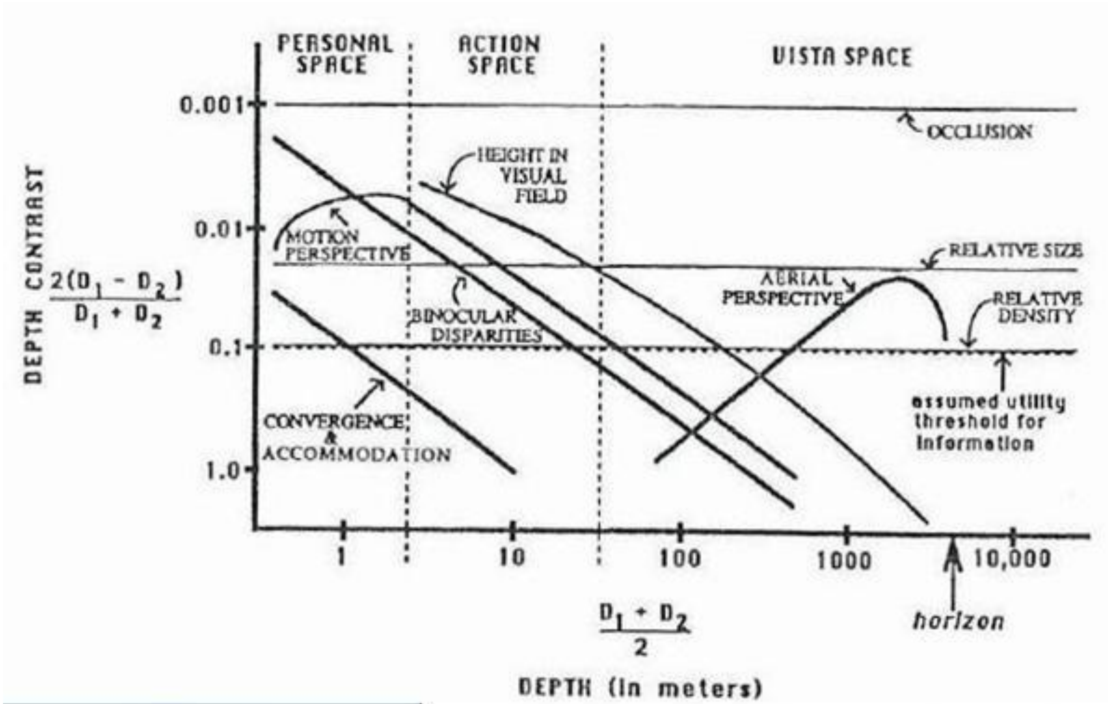


Figure 2.1. Graph of different sources of depth information. As the distances change, the effects of cues are also changing. (Cutting and Vishton, 1995, p. 80)

Besides accommodation, when pictorial depth cues are taken into consideration, *size* is one of the influencing factors of distance perception. From the Figure 2.1. it can easily be seen that it has a continuous effect on depth perception. Size and distance are closely related with each other since the size of the retinal image changes according to the variation between the observer and the distance of the object (Ittelson, 1960). However, without any other cue, retinal image may not give the correct size of the object. Therefore, *familiar size* and *relative size* are the effective cues for distance perception (Sekular and Blake, 1994). When someone always perceives an object according to its environment some simultaneous effects such as a line looking longer near a shorter one close to it occurs (Gombos and Schanda, 2006). This is the case when a familiar sized object appears near an unfamiliar one, so an individual can use this clue to detect the sizes of objects relatively to each other as well as their *relative distances*. Furthermore, the farther an object from the observer, the smaller it will appear because the retinal image that is going to be created will be smaller (Michel, 1996). In this manner, size cue converges with *linear perspective* as the appearance of spatial depth becomes exceptionally strong because of the field of view (Michel, 1996).

The main idea in *linear perspective* is that parallel lines appear to meet in the distance while creating a horizon line at the end (Matlin and Foley, 1997). According to *linear perspective* cue, the covered portion of the retina gets smaller when the image is closer to the horizon (and farther from the observer) (see Figure 2.2).

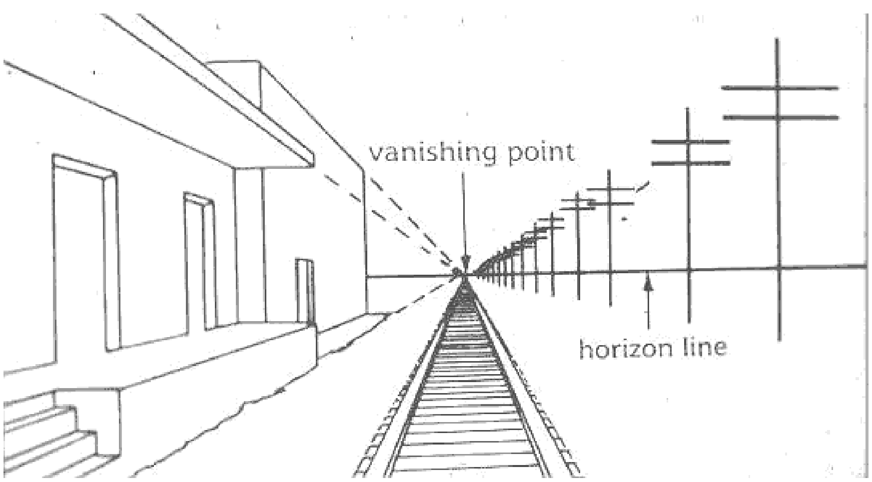


Figure 2.2. Linear perspective cue.

From:http://www1.appstate.edu/~kms/classes/psy3203/MonocularDepth/linear.gif

Michel (1996) states that linear perspective is the strongest depth cue which can be used to create powerful spatial depth. Cook, Yutsudo, Fujimoto and Murata (2008) add that the density of linear perspective grid lines induces the effect of shadows, texture and color information of the illusion that are produced on depth perception. With respect to the linear perspective, the effects on perceiving depth are strongly influenced by the pictorial cues of *shading and shadows* of objects on the background and on other objects (Cook et al., 2008).

Shade and shadows are also important cues for the appearance of three-dimensionality and solidity of the objects with regard to the degree of darkness of it as well as perception of depth (Matlin and Foley, 1997; Wyburn, 1964) (see Figure 2.3).

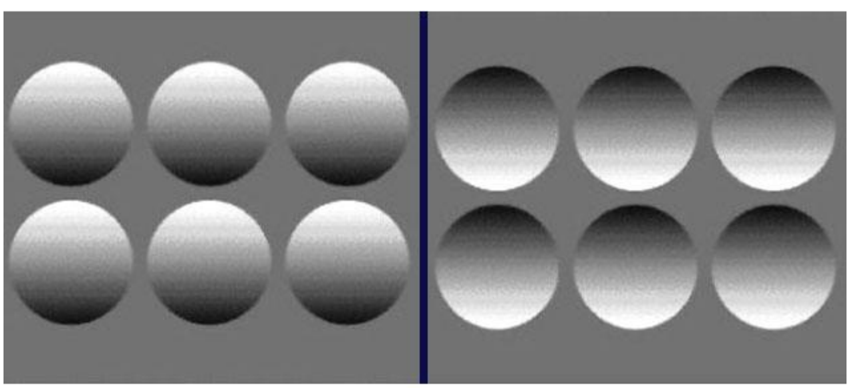


Figure 2.3. Highlights and shadows provide information about depth. The shadows indicate that the left hand image is convex, whereas the right hand image appears concave.

From: http://webvision.med.utah.edu/imageswv/KallDepth5.jpg

In this manner, the interaction of direction of light and the shape of object produces the shadow and gives information about the spatial depth as mentioned by Michel (1996). *Light and shade* tools play an important role in differentiating foreground and background from each other and perceiving the spatial layout (Cutting and Vishton, 1995). Shadows can also give crucial data when it is conveyed in relation with another cue of depth perception such as texture (Michel, 1996; Sekular and Blake, 1994).

Texture gradient is another depth cue that gives clues for the perception of layout and our environment. “There are at least three gradients of texture in surfaces receding in depth-depth gradients of size, density and compression” (Cutting and Vishton, 1995, p.94). Cutting and Vishton (1995) explain the effect of size gradient (the change in the largest extent of texture element) as similar with relative size which has a continuous impact on many elements across a surface (see Figure 2.1).

Besides, texture density gradient is defined as the “homogenously distributed markings [...]” (Steven, 1988, p. 199) and as the distance is increased, the density gets higher in the visual field. Dissimilarly, according to Cutting and Vishton (1995), the compression gradient, which refers to the shape of the texture gradient, is ineffective on depth perception; however, it gives good information about object shape and curvilinearity. Furthermore, with respect to Palmer and Brooks (2008) experiment, moving, sharp or red textures (as opposed to stationary, blurred and green) are seen closer.

Another cue that is also affected by blurriness and color is *aerial perspective*. It is the atmospheric effect that creates another kind of perspective because of the relative amount of moisture and pollution. Accordingly, with the high degree of these ingredients, “objects in the distance become bluer and decreased in contrast with respect to objects in the foreground” (Cutting and Vishton, 1995, p. 88). In a way, distance causes loss of detail and color in a scene (Steven, 1988). However, this is an effective depth cue in exterior spaces, not in interiors.

Another cue of depth perception, *interposition (occlusion),* is mentioned as if an object appears to overlap with or be a cut off part of another object it tends to appear nearer (Matlin and Foley, 1997; Wyburn, 1964). Besides, the relative sharpness of outline is also given as a cue for perceiving depth by Wyburn (1964). Michel (1996) explains this phenomenon as “when one object or surface is overlapped by another, the one with continuous outer contour appears to be in front and closer” (p. 25). This is one of the most important cues of depth; it also has an important role in the binocular disparity process that will be discussed later in section 2.1.1.2 (Matlin and Foley, 1997).

In addition to all of these cues, Payne (1964) considers *color* as a cue for distance perception. He (1964) mentions *color* as a dependent variable of distance perception although cues of aerial perspective or light and shade can be considered to be some characteristics of color. Studies conducted about the effects of color on depth perception are going to be mentioned broadly later in Section 3.2.

2.1.1.2. Binocular Depth Cues

Another set of cues comes from the fact that individuals have two eyes. Besides all the monocular cues that have been discussed above, there are convergence and divergence, *binocular disparity* and *color stereopsis* cues that can be investigated under the title of binocular depth cues (Coren, Ward and Enns, 1994).

According to binocular vision, eye movements occur to focus the image on two foveae. The movements of two eyes towards different direction are called *vergence movements*. If this movement is inwards (towards the nose), it is called *convergence*. The opposite movement (away from each other), which occurs because the target is farther away, is called *divergence* (Coren et. at., 1994). Both the convergence and divergence are measured by the angles between the optical axes of the two eyes. It is suggested that in the range of up to only 2 m, convergence can be taken as the only source of information for depth. Nevertheless, it is not effective enough to perceive distances correctly at great distances only with convergence (Cutting and Vishton, 1995), Williams and Tresilian (1999) mention a conflicting result that with the additional depth cues, the contribution of vergence information becomes complicated. The complexity which is created by the combinations of cues, can cause unexpected distortions of visual space. For instance, the distances of objects and points can be perceived closer or further than they actually are. Moreover, vergence and accommodation are generally noted as cross couple, in the way that accommodation influences depth perception indirectly via its effect on vergence (Williams and Tresilian, 1999).

Similarly, because individuals have two eyes in which pupils are roughly apart up to 6.5 cm, slightly different images of the environment occur in each eye. The difference between the two eyes' images is called *binocular disparity* (Coren et.al., 1994). If the object is in front of the fixation plane, it is *crossed disparity* because, in order to fixate on the object, the eyes must cross. However, the objects behind the fixation plane create *uncrossed disparity* (Matlin and Foley, 1997). When the distance to the fixation plane increases, the disparities between the images of two eyes decrease. With all of those cues, binocular disparity "[…] provides the information needed to judge depth binocularly, an ability known as *stereopsis*" (Matlin and Foley, 1997, p. 183). *Stereopsis* allows individuals to judge relative depth with great accuracy while making them see the objects that are invisible to either eye alone (Sekular and Blake, 1994).

Some of the stereoscopic effects are mentioned in Form-And- Color-And- Depth (FACADE) theory of Grossberg (1994). According to this theory, different depth cues are investigated interactively under binocular and monocular conditions. According to the interactions of 3D boundary segmentations of edge, texture, shading and stereo information with filling-in surface properties of brightness, color and depth, the system of binocular viewing is analyzed in FACADE theory (Grossberg, 1994). As the main idea of the theory, pictorial cues are mentioned as activating several types of interaction processes in cortical mechanism that gives rise to three-dimensional scenic percepts (Dresp, Durand and Grossberg, 2002).

Considering the FACADE theory of Grossberg (1994), studies are focused on the interaction between interposition and color and texture, in the manner of understanding the figure-ground separation in depth perception in visual cortex, by examining binocular conditions. With regard to some of the studies, occlusion provides the most important cue for depth perception; however, its interaction with different depth cues is inevitable (Dresp et. al., 2002). Although, Bailey et al. (2006) claim that "perspective cues such as relative size, occlusion and distance to the horizon are generally more effective at conveying depth than shading, luminance and colour" (p. 2), Dresp et. al. (2002) mention that interposition and occlusion on their own are not strong enough to compete with a strong, conflicting contrast cue. Thus, "interposition and partial occlusion contribute to generate perceived depth when combined with a cooperative contrast cue" (Dresp et al., 2002, p. 273). Likewise, Dresp and Guibal (2004) report that partial occlusion and interposition compete with luminance contrast of red color and achromatic contrast. Besides luminance, color and contrast interactions with occlusion, texture is also studied as another component of FACADE theory. Kawabe and Miura (2006) stat that the texture edges of interposition or occlusion contribute to depth perception. In their experiment (2006), which indicates the two cues of occlusion and texture together, it is mentioned that the image with textures of random stripes is seen nearer than the textured image of constant stripes.

Additionally, due to the effect of color in binocular vision, differences in depth perception occur and it is known as *color stereopsis,* which acts as another binocular cue of depth perception (Matlin and Foley, 1997). These differences can occur depending on the brightness, saturation and hue attributes of color. Furthermore, color stereopsis is also studied considering figure-ground relations which affords opposite effects on depth perception (Dengler and Nitschke, 1993). Those effects of color are discussed in detail in Section 3.2.

3. COLOR AND LIGHT

In this section, general definitions of color and light are given. Basic terms determining color and its attributes, besides light and its effect on color, are focused on. After the definitions, color and light effects on depth perception are going to be discussed in detail.

3.1. Color Appearance

In this section, the definitions of color appearance in visual perception are presented in order to understand the fundamental scientific concepts of color. Color appearance is generally considered together with the parameters of *hue, saturation* and *brightness* of the visual stimuli that are displayed in the observer's field of view. The colored visual stimulus that is observed by the viewer is specified by the physical details of spatial properties (size, shape, and location in the visual field) and temporal properties (steady state, moving, pulsing) and their radiant power distributions (spectral power distribution) (Boff et al. et al., 1986). The color appearance of the visual stimulus derives from the experience that the observer gets and the judgment of color appearance is directly influenced by the conditions and the environment that the visual stimuli are presented in. Nevertheless, expressing the perceived stimulus has a complicated nature in itself; therefore, there are some mathematical models designed to describe the color appearance precisely and universally.

According to the *Commission International de l'Éclairage* (CIE), color can be defined as an "attribute of visual perception consisting of any combination of *chromatic or achromatic* content" (Fairchild, 2005, p. 84) which can be named by *chromatic colors* as yellow, orange, green etc. or *achromatic colors* as white, gray, black etc., and it can be defined by the adjectives of dim, light, dark etc. Besides, perceived color depends on "the spectral composition of the radiant energy concerned by the observer" (Boff et al., 1986, p. 9-2) according to the size, shape and surrounding of the stimulus areas. These stimulus areas can be both compared to each other as *related colors* or can be just judged as *unrelated colors* in which the circumstances will differ, and so their appearance will also differ from each other. Moreover, it is important to notice the difference between the more specified uses of related colors as object color, surface color and light color. In this research, both the use of surface and light colors are going to carry importance.

3.1.1. Attributes of Color

As it was defined before, color mainly deals with three basic attributes called *hue, brightness* and *saturation* (Fairchild, 2005) (see Figure 3.1).

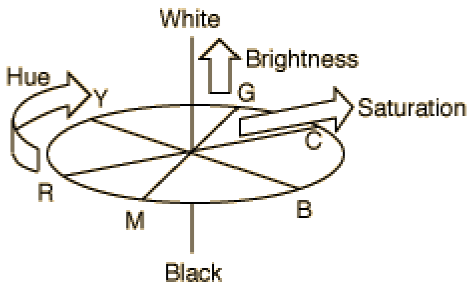


Figure 3.1. Color attributes (Michel, 1996, p.171).

Referring to the literature according to their use and concepts, instead of brightness, *lightness* can be used or instead of saturation, *chroma* can be used to identify colors. However, in some research these words mean different impositions with regard to the conditions and designs of the research.

Firstly, *hue* is used as an attribute of visual sensation to characterize the name of colors as red, yellow, green and blue which cannot be described other than its own (Fairchild,2005). These four colors are the *unique hues* that are used in combinations to name the *hueness* of the other color stimulus like orange (yellowish red or reddish yellow) (Boff et al., 1986). *Hue* is also understood as the variation in color when the wavelength is changed (Padgham and Saunders, 1975).

Secondly, *brightness* is the aspect of visual sensation which determines the level of emitted light from an area (Fairchild, 2005). It is also defined as the variations in perception with the change in intensity (Michel, 1996; Boff et al., 1986). These variation ranges in brightness can be from very bright to very dim. Although in some cases *lightness* is used as brightness, the specific definition of it is "the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitted" (Fairchild, 2005, p. 86). In this sense, lightness can be referred to as *relative brightness*.

Additionally, the terms *saturation* and *chroma* are perhaps the most contentious in the literature of color appearance. *Chroma* is one of the factors in color appearance which involves a judgment between a chromatic color and an achromatic color of the same lightness (Boff et al., 1986). It is the "colorfulness of an area judged as a proportion of brightness of a similarly illuminated area that appears white or highly saturated" (Fairchild, 2005, p.87). It can be called the *relative colorfulness*; it approximately stays constant across the changes of luminance levels on the surfaces or objects which have the same hue. *Saturation* can be defined as *relative colorfulness* as well; however, it is relative to its own brightness, where *chroma* is "the relative to the brightness of a similarly illuminated area that appears white." (Fairchild, 2005, p. 88). At the same time *saturation* "[…] permits a judgment to be made of the degree to which a chromatic color differs from an achromatic color regardless of their lightness" (Boff et al., 1986, p. 9-4).

3.1.2. Attributes of Light

As an effective factor in color, basic knowledge of light should also be mentioned in order to have the right explanations of visual perception and color appearance. Light is a form of radiant energy which generates a range of *electromagnetic spectrum* (Zukauskas, Shur and Gaska, 2002). The visible radiant energy occupies a small part of this electromagnetic spectrum which is called *visible spectrum*. Essentially, the light range of the spectrum is the only range of the electromagnetic spectrum which acts like stimuli for the visual system to respond (Zukauskas et. al, 2002). The electromagnetic radiation is generally defined with *a wavelength* whose unit of length is *nanometer* (nm). The visible light spectrum includes the wavelength ranging between 380 and 780 nm. Between these ranges of visible spectrum, there are different hues perceived as light colors (Valberg, 2005). Light which is made of a single wavelength is called *monochromatic light,* which has the maximum saturation of color in the visible spectrum (Agoston, 1987).

In the real world, most of the light that is perceived is not monochromatic. A light coming from any lighting source will contain nearly half of the visible spectrum; however, it will be perceived as one hue because of the amount of that hue in the light. For example, green beam in 500-550 nm region of spectrum has a larger amount of green in the light than blue, so it will be perceived to be greener than the light which is in 400-500 nm region of the spectrum that has larger amounts of blue in it. These amounts of radiant energy (power) in the visible range of 380-780 nm can be measured by *spectroradiometer* in the manner of wavelength interval (portion) of light (Agoston, 1987).

The hues in the visible spectrum are called *spectral colors*. Besides these spectral colors, there are some other colors that can be experienced but do not exist in any of the sources' spectrum as monochromatic radiation; they are known as *nonspectral colors*. This portion of colors has purple, purplish red and a range of colors which are neighboring red hues. They can be produced by combining the monochromatic colors (Agoston, 1987).

Light in our environment is not monochromatic all the time, and its characteristics are related to its source. Every light source has its own rate of radiant energy (power) emitted in wavelength intervals in the visible range of the spectrum. Each light source can be evaluated according to its spectral power, which is related to its radiant energy, and its effect distribution in wavelength intervals. The relation between spectral power and effect distribution is defined as *spectral power distribution* which defines the characteristic of a light source (Valberg, 2005).

There is also a standardization of light sources which is known as *illuminants* and it is generated by CIE according to their spectral power distributions. Illuminant A, D65 and F2 are some of these CIE standardized illuminants which represent a typical incandescent light, daylight and fluorescent light, respectively (Fairchild, 2005). Each of these CIE illuminants are also standardized according to their *color temperature* which is another descriptive characteristic of a light source. It is a physical characteristic of light which is referenced from a special type of theoretical light source, known as *black-*

body radiator. "*The black body radiator* emits light with intensity and spectral distribution depending on the temperature of the material" (Valberg, 2005, p. 38) and this temperature is originally called *color temperature*. When the temperature of the radiator increass, the wavelength becomes shorter. The unit of the color temperature is generated in Kelvin and the visible light begins to appear around 1000 K. A tungsten filament lamp can be considered to be the closest to black body radiator; however, as it is generally not possible to obtain the exact required laboratory conditions of black body radiator in the environment, *correlated color temperature* is generally used for defining light sources (Fairchild, 2005). The CCT is the color temperature of a light source that has almost the same color as the black body radiator.

The CCT is mostly used to define the color of white light and it has its locus on the *CIE chromaticity coordinates*, so its values can easily be estimated from there. CIE chromaticity diagram is an industry standard and a common way of visualizing a perceived color according to its CIE tristimulus values (see Figure 3.2).

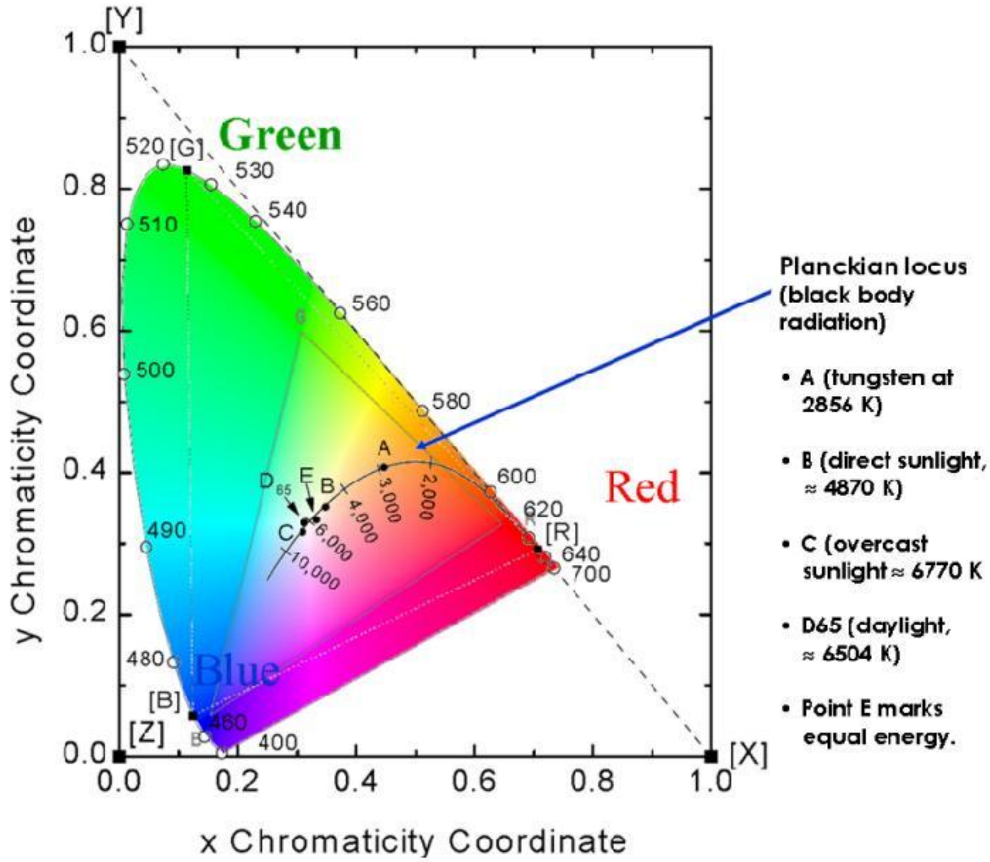


Figure 3.2.The CIE 1931 Chromaticity diagram. The outer horseshoe shaped edge represents the wavelengths of spectral colors. The horizontal axis represents the *x* values and the vertical axis represents the *y* values. Any color inside the horseshoe shape has its coordinate with *x* and *y* values. (Zukauskas et. al, 2002)

Besides correlated color temperature, it is also possible to control different wavelength components of light in order to create different colors of light with different chromaticity coordinates (Zukauskas et. al, 2002). Different colors can be created by producing different spectra. However, the important thing here is to consider that these different colors of light can have similar CCTs on the CIE chromaticity diagram, while having different *x* and *y* values (Valberg, 2005). Therefore, care should be taken when one specifies a light source by CCT only, which can be very misleading.

To understand all the qualities of light, some other measures of it should also be known like *intensity, illuminance* and *luminance*. *Intensity* is the amount of radiant energy transferred per unit area. It is separated into two in light engineering as *illuminance* and *luminance* in order to express the amount of light. *Illuminance* (lm/m2) tells how much light flux enters a unit area according to the distance between the source and the illuminated area. Accordingly, “the *luminance* (cd/m2) of a surface tells us how much light reaches the retina from that surface when the object is imaged through the eye media” (Valberg, 2005, p. 169). These measures also have some effects on the attributes of color, especially on brightness, which are going to be mentioned in the next section. As light has the greatest importance on appearance of surface and object colors, the next section is going to deal with light effects on color and its parameters.

3.1.3. Effects of Light on Attributes of Visual Sensation

Until now the factors and parameters in the environment that affect the individual’s visual perception have been discussed. Light is the primary factor which makes all other parameters visible by reflection, absorption or transmission from the surfaces. All the other parameters are additional collateral factors that help individuals to understand their environment and make them perceive their surrounding in detail and with more information. In that sense, texture, color and shades are the ones which give information about surfaces where size, perspective and occlusion determine some relations among different surfaces, objects and spaces. As it is mentioned before, those cues are also used as sources of information interacting with each other. According to the light source and with different combinations of those cues, different surroundings can be created and different appearances of colors, and accordingly different appearances of spaces can be obtained. In this section, characteristics of light source and the surrounding of the colored object are going to be taken into account and how the appearance of color changes is going to be discussed. Color has three basic attributes, each of which is mentioned under a separate title.

3.1.3.1. Effects on Hue

As the surrounding of the observed color stimuli carries importance on how it appears and is perceived, the below phenomena are important in order to have an idea about the effects of light and color on each other. This information may also carry importance for the design of the stimulus in the study.

For the color appearance attribute of hue, a shift occurs after adding white light into a monochromatic light by making it vary in purity and this phenomenon is known as *Abney Effect*. According to this phenomenon, Johnson and Fairchild (2005) mention that it is not possible to judge hue parameter of color just by its wavelength since its colorimetric purity changes as the dominant wavelength stays constant. Therefore, in the chromaticity diagram, the straight lines from the white point to the spectral locus are not lines of constant hue (Fairchild, 2005).

Another similar phenomenon which deals with the changes in hue perception is *Bezold-Brücke shift*. This time the reason of the change in hue is the variation in intensity. This is also a reasonable effect that displays wavelength of monochromatic light as not the only indicator of the perceived hue. Padgham and Saunders (1975) claim that with the increase in luminance, the hue of red becomes yellower and violet becomes bluer. Bezold-Brücke shift differs from Abney effect in because its validity is just for unrelated colors which are seen in isolation from other colors. Hunt has proved that this shift is not valid for related colors which are "[…] perceived to belong to an area or […] seen in relation to other colors" as cited in Fairchild (2005, p.89).

Pridmore (2007) has conducted some studies concentrating on Abney and Bezold-Brücke effects. He notes that this hue shift is an effective factor in perceiving three-dimensional object shape in the manner of adding hue and lightness differences to its color. According to him, these two effects are directly related to each other depending on the increase in chroma when the lightness gets higher. This is explained with the combination of these two effects, the physical features of an object becomes more definite and the object is perceived more three dimensionally; thereby, all three attributes of color work together to determine the features of the shape of an object.

3.1.3.2. Effects on Brightness

One of the parameters that is defined by the Y tristimulus value in CIE system of colorimetry as luminance level is brightness. In fact, most of the time it is assumed that brightness is the function of luminance level; however, when *Helmholtz-Kohlrausch effect* is taken into consideration, this is not the case. According to *Helmholtz-Kohlrausch effect*, there is a change occurring in perceived brightness with the increase in purity of the colored stimuli when its luminance is kept constant in the photopic range (CIE, 1988). With reference to this effect, the stimulus appears brighter at a constant luminance if the saturation is increased (Johnson and Fairchild, 2005). Furthermore, Fairchild (2005) claims that this effect is also dependent to the hue of stimulus besides the saturation. Thus, it is less noticeable for yellow than purples.

In addition, another effect on brightness which occurs with changes in the illumination level is *Purkinje shift*. According to *Purkinje shift*, when the light level decreases, because of the optical ability of the human eye, the peak sensitivity shifts towards the blue end of the color spectrum (Fairchild, 2005). *Purkinje shift* is related to the adaptation of the human eye and receptor cells in the retina. Because of the visual functioning of rod and cone cells, in low levels of luminance (less than 0.01 cd/m^2) known as scotopic vision, sensitivity to shorterwavelenghts increases (Fairchild, 2005). Anstis (2002) has conducted experiments on light effects on Purkinje shift, and he mentions that because of the switch from cone vision to rod vision through dark-adaptation, with the visual sensitivity, blue colors look relatively lighter than red colors.

Another basic effect that is known as *Stevens effect* examines luminance variations and brightness contrast. Regarding the experiments, it is known that depending on an increase in luminance level, brightness contrast also increases, and apparently dark colors appear darker and light colors appear lighter when luminance level is increased. According to *Stevens effect*, a power function is cited between perceived brightness and measured luminance, which is known as Stevens power law in psychophysics. It shows the estimations of an average relative brightness magnitude as a function of relative luminance for different adaptation levels (Fairchild, 2005).

As it was mentioned before, to do a color matching between stimuli, some conditions should be provided equally. If surrounding or background conditions in two settings are not the same, in manner of luminance levels, a shift of brightness perception named *simultaneous contrast* occurs. It can simply be explained as the change in a surface color appearance caused by an adjacent surface which is brighter or darker than the other (Michel, 1996). Figure 3.3 illustrates an example of simultaneous contrast. While the top two small gray square patches are perceived to be the same, the one on the white background looks darker and the one on the black background looks lighter.

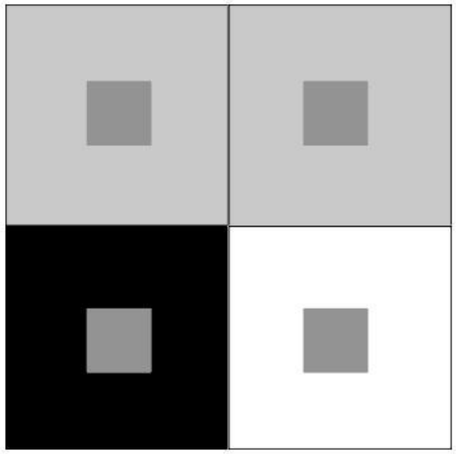


Figure 3.3. Simultaneous contrast (Achromatic). (Fairchild, 2005, p. 112)

Color changes in simultaneous contrast follow the *opponent theory* of vision, which mentions the cones system as processing according to three opponent channels of red versus green, blue versus yellow and black versus white (Fairchild,2005). Therefore, simultaneous contrast can also be seen in chromatic colors and “a red background would tend to induce a green color shift, a green would induce a red, a blue induces yellow, and yellow induces blue” (see Figure 3.4) (Johnson and Fairchild, 2005, p. 42).

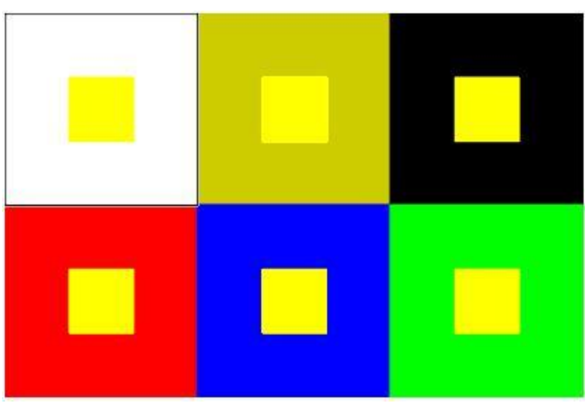


Figure 3.4. Simultaneous contrast (Chromatic).

Lastly, *Bartleson- Breneman effect* also deals with the variation in luminance level and the effect of surround on complex stimuli. Bartleson and Breneman observed some differences in perception of contrast when the luminance level of a stimulus' surround is changed. As the luminance of the surround is increased, perceived contrast also increased because "when an image is viewed in a dark surround, black colors look lighter while the light colors remain relatively constant" (Johnson and Fairchild, 2005, p. 52). However, black colors start to look darker when the luminance is increased and it causes overall view to appear in higher contrast.

The level of illuminance and luminance are both effective factors in perceived brightness as well as spatial structure and background of the stimulus. By increasing and decreasing the level of the light source, or creating different combinations of luminance levels, the appearance of an image or a stimulus object dramatically changes.

3.1.3.3. Effects on Saturation

Similar to the effects on hue and brightness, luminance level and color of illumination are also important factors in perceiving the saturation of a stimulus in relation to its surround. One of the effects which deal with perceived saturation is *Hunt effect*. To observe that effect, Hunt used a haploscopic matching, in which the viewer considers two different stimuli conditions in his two eyes and tries to adjust their color in order to obtain equal colorimetric purity (Fairchild, 2005). As a result, to equalize the saturation of a low luminance surrounding with a high luminance one, there is much more colorimetric purity required. Hunt (1952) mentions in his results that “at high levels of adapting light intensity, increasing the test color intensity caused most colors to become bluer” (p.49). These results highlight the fact that luminance level is an influencing factor in perceived saturation, as it is for brightness (Johnson and Fairchild, 2005). According to that effect, chromatic contrast of the stimulus increases when the brightness of surround increases.

All of these effects of luminance and illuminance, considering the environmental constraints of the stimuli are significant factors in perceiving color in the visual world. Therefore, they are of great importance for this study, and the design of the experimental set-up takes into account these effects of light and surrounding on color appearance of spaces, in relation to the appearance of surfaces.

3.2. Color in Depth Perception

Color of the objects has a considerable effect on depth perception in the visual field (Dresp and Guibal, 2004). In that sense, it is one of the most commonly debated cues, about which there are critical works (Sundet, 1978). This section is going to cover these works which concern the cues of depth perception and color attributes which affect the perception of depth. Color attributes consist of hue, brightness and saturation. Besides these parameters, the source (light), which makes the color occur in the visible environment, has also been mentioned in the following sections.

3.2.1. Effects of Hue, Brightness and Saturation on Depth Perception

As Sundet (1978) mentions the effect of color on objects' apparent distances has long been known. This situation has mostly been practiced with "highly saturated colors and with objects lying near each other" (Sundet, 1978, p. 133). One of the earliest and well-known studies on this subject was conducted by Luckiesh (1918) with the letters of red 'X' and blue 'E' by asking the participants to move the letters back and forth in an apparatus until they came on to the same plane. He used tungsten lamp to illuminate the letters and the boxes were equipped with blue and red filters in order to obtain the colored view. In the study, as the advancing quality of the red, most of the time red 'X' was moved by the participants further away in order to make it appear on the same plane with blue 'E'.

This phenomenon has been explained by Sundet (1978) with an optical case, under two parameters of depth perception, namely monocular and binocular. About the monocular theory, Sundet (1978) states that short-wave light refracts in the eye's optical media more than long-wave light, and because of this phenomenon, the equidistant sources of different colors cannot be simultaneously focused on the retina, which is called *chromatic aberration*. According to *chromatic aberration*, a short-wave light source occurs nearer than a long-wave light source (see Figure 3.5).

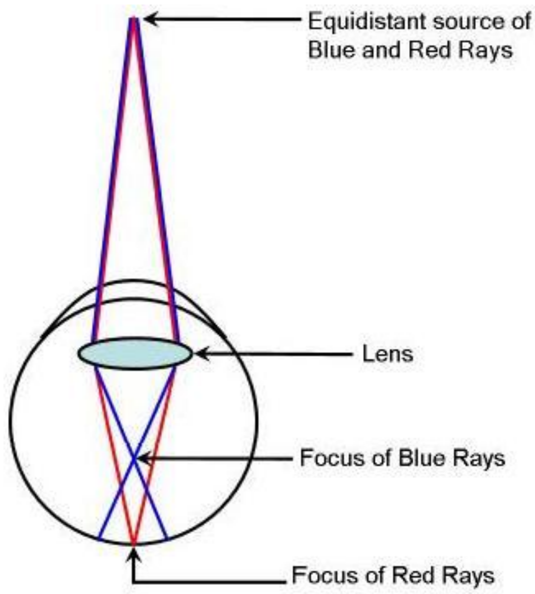


Figure 3.5. Chromatic aberration. (Sundet, 1987, p.134)

Besides, Sundet (1978) points out that all theories of binocular color-distance have chromatic aberration in common and this is taken the point of departure. From the chromatic aberration phenomenon, it is well understood that, wavelength is a stimulus that affects its perceived depth.

As wavelength of the colors refers to their hue, the studies on hues of colors and their relation to distance perception are taken into consideration in this part. Before Sundet (1978) gave the information that colors in themselves have the quality of depth because of the refraction in the eye, Edwards (1955) mentioned in the conclusion of his experiment that there is no significant evidence of color itself having the quality of depth. However, training and association may lead to seeing of some colors as near or far and may provide effective use of color in art for the expression of depth. In opposition to Edwards (1955), Egusa (1983) explains an effect of hue on perceived depth as green and blue difference is smaller than the red and green one, in which the red one appears nearer.

Furthermore, in the first outdoor study, Mount, et. al. (1956) also mention the hue effects on distance perception. In the experiment, they have compared equal brightness of coloured and gray papers under sunlight. According to the results, they (1956) express that each color is judged nearer than gray that has equal brightness, and the hues appeared closer when viewed against the dark rather than in light. Additionally, Dengler and Nitschke (1993) mention that when four colors (red, yellow, green and blue) are seen in front of the black background, long-wavelength colors appear in the front; however, in front of the white background, the depth perception of colors are reversed. In that sense, brightness of the background of a stimulus affects depth perception of the colors as well. However, there is still a gap on the depth perception of different hue combinations in terms of the stimuli and the background. Besides that, Mount et. al. (1956) also point out that saturation and brightness contrast are more effective on depth perception than the difference in distance perception of one hue over the other.

As another parameter of color, saturation is also mentioned in many studies. In general, as Sundet (1978) remarks, high saturated colors are used in the experiments. According to Mount et al. (1956), the apparent position of a color is advanced when the saturation of its color is increased in contrast to its background. In this manner, it can be understood that the saturation difference between the stimulus and the surrounding also bears importance for depth perception. Besides, Egusa (1983) notes that if the higher saturated color is red or green, they are judged nearer, but such an effect cannot be seen with blue color. In a more recent study conducted by Bailey et.al. (2006) with different coloured three dimensional objects of teapots and backgrounds on the computer screen, it is pointed out that similar results with high saturated warm or cool colors are obtained with less saturated colors in apparent distance perception.

Camgöz, Yener and Güvenç (2004) name saturation as the secondary attribute of color in judgment of 'nearness', whereas the brightness is the most dominant attribute. The apparent brightness and brightness contrast are also one of the most commonly studied cues in depth perception. In Michel's (1996) book, the aspect of perceiving brightness is said to be *gamma movement*. *Gamma movement* is explained by Michel (1996) as follows: as the object brightness is increased, the object "[…] appears to advance toward the viewer from its initial fixation point […] it returns to its former position" (p. 12) when brightness is decreased.

The relation of brightness with colored object distance perception was explained as insistency quality of color by Katz in 1935, which is cited in Payne (1964). He (1964) describes the insistency of a color as the power of a color to catch the eye and hold it steadily, and he added that the insistent color appears nearer. Sundet (1978) comments on that statement that the perceived relative distance may be affected by relative brightness of the colored objects.

In another study considering the brightness effect on depth perception, Taylor and Sumner (1945) use fluorescent lamps and colored papers (red, yellow, green, blue, white, black and neutral gray) in different brightness levels. Although the papers are in different colors, Taylor and Sumner's (1945) focus is on the brightness differences. In the experiment, they observe that the bright colored papers are drawn farther in the apparatus in order to equalize their apparent distances to each other. Thus, they state that at a constant distance light colors appear nearer than dark colors. Furthermore, in another study by Johns and Sumner (1948) which was conducted to verify the study of Taylor and Sumner (1945), the same result of bright colors appearing nearer than dark colors at the constant distance is obtained. According to the results, the order of the colors from the one that appears nearest to the one that appears farthest is red, white, yellow, green, blue and black. For this experiment, it is noted that the cues which the subjects use to make the equalization are relative sharpness of the vertical edges and relative thickness of the colored papers, which are going to be the cues that the participants will focus on in our experiment as well.

The brightness effect also appears to be one of the contrast differences in adjacent colours referring to stimuli-surrounding relation. Payne (1964) mentions that if a colour differs from the background more, it stands farther away from the background. Thus, one of the two colours which is more similar to the background will appear more distant than the other. In a similar way, Ichihara et. al. (2007) claim that contrast is an important cue for perceiving the depth of an object. It creates some illusions on the appearance of colored surfaces in the manner of depth perception (Michel, 1996). Ichihara et. al. (2007) divide contrast into two as area contrast and texture contrast. They (2007) define *area contrast* as “the difference between the average luminance of the surface area of an object and the average luminance of the background” (p. 686). When area contrast is low, the object looks far from the observer; similarly, it looks near when the contrast is high. Grandis (1986) defines *simultaneous* or *reciprocal contrast*, which was particularly explained in the Section 3.1.3.2, as two areas of high contrast in adjacent positions altering the appearance of both. As Grandis (1986) says a light area next to a dark area appears lighter than it really is. Thus, this simultaneous contrast has the effect of darkening the dark color and lightening the light color more. The effect of two colors on each other makes lighter one to be perceived nearer than they are as an effect of *color kinetics*. He explains *color kinetics* in relation with simultaneous contrast. He mentions *color kinetics* as a property which makes color to appear in the front or back rather than at its real location. Moreover, he continues by saying that this effect may be because of the degree of luminosity of each color under lighting.

The literature on brightness, darkness and contrast effects of colors has also been searched under the subject of spaciousness and room size of the space. Taylor and Sumner (1945) state that rooms done in white, light yellow, light green would appear smaller than they really are. However, Mahnke (1996) claim that light or pale colors recede and increase the apparent room size whereas dark or saturated colors decrease the apparent size of the room. Clearwater (1986) mentions that depth perception studies which are conducted with apparatus are also done by full-scaled room with movable walls. She (1986) adds that researchers have studied brightness effect alone; hue and saturation levels of the colors have been controlled in full-scaled studies. She (1986) claims that “apparently, a lightly colored space appears larger, and there is a recession of blue that is highly dependent on its saturation” (p. 76). Michel (1996) also mentions that regardless of its physical size, a bright room is perceived as more spacious.

3.2.2. Effect of Light on Depth Perception

As it is intensively mentioned many times, for the appearance of surface colors, illumination has a great importance because light makes colors and surfaces visible. Color and light are the parameters which are specified simultaneously while color is also involved in light itself. Thus, the surface has the property of absorbing, reflecting and refracting the light with respect to generating its color. This relation between illuminance of light and color is mentioned by Yamauchi and Uchikawa (2005) in that the perceived color of an illuminated surface which is observed from a small window changes when the intensity of the illumination increases. The color appears opaque and right on the small window without any depth when the intensity of the illumination is low, and the color appears brighter and distant as the intensity of the illumination increases.

Coules (1955) has also set an experiment including illuminated opal glass discs with different intensity levels in order to understand the brightness effect on both monocular and binocular viewing. He (1955) states that both under monocular and binocular conditions, brightness influences judgment of distance. He (1955) mentions that in binocular viewing, the subject who has right eye dominance judges the light stimulus on his right to be nearer although it is in fact farther. Similarly, it is observed that the subject with left eye dominance judges that the light stimulus on the left is nearer.

The most basic distance perception experiment with colored light sources has been done by Pillsbury and Schaefer (1937). In the experiment, they use red neon or blue neon and argon lights which the participants can view through artificial pupil like slits. The participants view the different colored lights monocularly and judge their distances. According to the result, Pillsbury and Schaefer (1937) state that even when they put blue light farther than the red light, blue light is judged nearer. This is an opposite result when compared to distance perception of colored surfaces in which the red one is generally perceived nearer than blue. This effect can be explained by Purkinje shift as blue light appears brighter than red at low luminance levels; however, in their paper there is no specific remark about the luminance level. Besides, there is a relation obtained between the color of stimulus and the intensity of its surrounding in the manner of depth perception by Dengler and Nitschke (1993). According to their (1993) studies, the short-wavelength colors are seen farther than long-wavelength colors when the intensity levels of these stimuli are greater than the intensity level of stimulus surrounding. This effect is reversed, when the lighting conditions are also reversed.

In recent years, some other experiments by Huang (2007) have been done on colored lights and depth matching tasks. In his experiment, he uses colored lights and colored surfaces in a box-like apparatus and he asks the participants to equalize the distances of the colored chips. The experiment has been done both with monocular and binocular viewing. According to the results, he mentions that the perceived distance difference in binocular viewing is significantly less than the monocular viewing because of the convergence and disparity manipulations on depth. Besides, he has found an effect of green light, under which there are more distance differences perceived than white and yellow light. Moreover, perceived distance under white light is less than blue light. With reference to these results, he determines a significant effect of colored light on distance perception. Upon another study, there were no significant differences obtained between blue and green light conditions, neither with yellow, red and white light conditions (Huang, 2009). However, he declares that since the five colored lights are used in different hues and intensities, it is not specifically known whether the results are due to hue or intensity variations. Referring to that, this study focuses on the hue attribute of color and its relation with its surrounding, in this case the background, in order to understand if hue difference has an effect on depth perception.

4. THE EXPERIMENT

4.1. Aim of the Study

The aim of the study is to understand the relationship of color with distance perception in interior spaces. To understand this relationship, different object and background color combinations are tested.

4.1.1. Research Questions

The research questions of study are as follows:

1. Are there any effects of colored light on distance perception in interior spaces?
2. Does background color affect depth perception of different colored objects?

4.1.2. Hypotheses

The hypotheses of the study are as follows:

1. There are depth perception differences between different backgrounds with different hues.
2. There are depth perception differences between different hue combinations of background and object.
3. There are depth perception differences between different color temperatures of white lit background according to the hue of the object in front of it.

4.2. Method of the Study

The method of the study is explained under the sections of sample group, experiment room and stimuli, and procedure. The information about experiment considering participants, stimuli and how the experiment is conducted can be followed in detail in the next three sections.

4.2.1. Sample Group

To the first phase of the study, 35 students who were having their internships in Philips Research Eindhoven, Netherlands participated. 4 of them were female and 31 of them were male. They had engineering or industrial design backgrounds with the ages between 22-29. They had little to no knowledge of color and depth cues, in order to avoid possible biases and the influence of personal experience. Additionally, the experiment was conducted in English due to having participants from different nationalities who were capable of speaking and understanding English. To the second phase, 21 students who had the most consistent results according to their responses to the questions from the first phase participated.

4.2.2. Experiment Room and Stimuli

The experiment was conducted in the Shoplab of Holst Center, at High Tech Campus, Eindhoven. The room had no exterior windows, however, had shop windows which looked out on an inside hall. Those windows were covered with curtains in order not to have any other light source inside the experiment room. The measures of the room were 11m x 6m and ceiling height was 2.6m. As the lab was designed as a shop, there were some shelves and cloth hangers; however, all the exhibited clothes were removed and all the side walls remained white during the experiment. Besides, stable furniture which was in the visual scene was covered with black curtains. The floor of the room was covered with gray carpet.

The room had eleven different types of lamps with several types of installations. The main installations in the room were LED and halogen spots, fluorescent and LED wallwashers and general lighting devices. For the experiment, LED wallwashers of ColorKinetics Colorblaze (Philips) were used. Three lights of nearly 1.80 meters which were containing 12 LED groups were installed in the ceiling and three other lights were installed at the bottom of the wall. Every LED group had a small colorful finger-like effect on the wall. In order to drive the lights, the LightMan program was used with DMX controller. The lights could be driven with given intensity levels of their white or RGB channels. The arrangements on light levels and color were done with dimming in those RGB channels. The main reason for choosing this room for the experiment was to have sufficient viewing distance from the stimuli and to have more uniform lighting conditions on the stimuli background.

The stimuli consisted of the background which was lit with the wallwashers and two objects were situated in front of it. During the experiment six different colors of wallwashers were used in the background: orange, blue, red, green, warm white (3000K) and cool white (6500K). These colors were chosen with reference to the previous studies in literature (Mount et. al, 1956; Pillsbury and Schaefer, 1937; Dresp and Guibal, 2004; Huang, 2009) and also to have equal numbers of cool and warm colors. In that sense, orange and red were the long-wavelength and warm colors, whereas blue and green were the short-middle-wavelength and cool colors. Besides, white light was taken as the control light color, where also if color temperature made any difference on depth perception was tested. In order to understand the hue effect, their lightness and chroma were matched as close as possible to each other. The matching of colors was done with 3000K white point as it also represented the eye adaptation level of color temperature in the experiment. The LCH (Lightness, Chroma and Hue) of the colors were measured with Photo Research Spectra Duo PR 680 and Macro Spectar MS-75 lens. The LCH values of the color can be seen in Table 4.1.

Table 4.1. The LCH values of six background colors.

Color of the Background	**Lightness**	**Chroma**	**Hue**	**Color of the Background**	**Lightness**	**Chroma**	**Hue**
Warm white	58.69	3.7	O	Red	59.54	54.79	10.13
Cool white	58.37	77.92	274	Blue	55.64	55.98	244.39
Orange	57.89	56.89	48.13	Green	58.68	54.76	168.34

During the experiment, 2 sets of background were shown to the participants with the same colored objects in both of the sets; one of the background set was cool white and the second one was a two colored pair of the six light colors which were previously mentioned (see Figures 4.1 and 4.2). In front of the background, 2 identical objects in the dimensions of 45cm x 45 cm were placed. In the experiment, three different colors of objects were used in orange, blue and gray (see Table 4.2). Again referring to the literature (Pillsbury and Schaefer, 1937; Sundet, 1978; Dresp and Guibal, 2004), red and blue were chosen as object colors; however, according to a more recent study conducted by Seuntiens and Vogels (2008) orange instead of red was evaluated as creating a cosier atmosphere, so it was more preferable by individuals for use in interior spaces. Besides, cases with gray objects were also tested in order to have a control group of colored objects.

Figure 4.1. The stimuli with cool white lit background and gray objects.

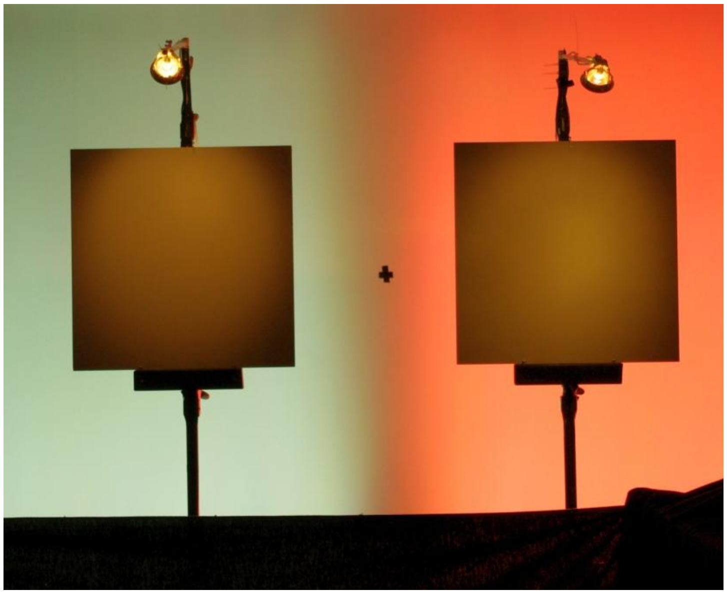


Figure 4.2. The stimuli with one color combination (red-blue) of background light and gray object.

Table 4.2. The LCH and NCS values of three object colors.

Color of the	Lightness	Chroma	Hue	NCS value
Orange	61	50	47	2050 Y60R
Blue	61	47	236	1060 B
Gray	59	0	0	5000 N

Those object colors were chosen from NCS according to their luminance and saturation values. The NCS codes of the colors were as follows: orange (2050- Y60R), blue (1060-B), gray (5000N). The colors of objects were also arranged as close as possible in their lightness and chroma to each other and to the six background colors in order to eliminate the effects of other color attributes and to find out specifically the effect of hue difference on distance perception. In the set-up, the two identical objects were also illuminated with spots which were fixated on top of the objects and could be moved in the same direction as the objects. They were two identical Philips Diamondline Halogen spots with 50 W, 12 V, 3000 K color temperature and 24º of angle to minimize shadows on the background.

The stimulus was seen from 10 m viewing distance with a chinrest by the participant in order to stabilize head movements (see Figure 4.3). 10 m viewing distance was provided for the experiment in order to avoid the undesired effects of depth cues which have already been displayed in Figure 2.1. Also, a black cross between the two objects was arranged for participants to focus their eye on to concentrate directly onto the colors but not to the size or shape of the objects while the distances of the objects were being changed by the experimenter. The participants were informed before the experiment about where to focus and why.

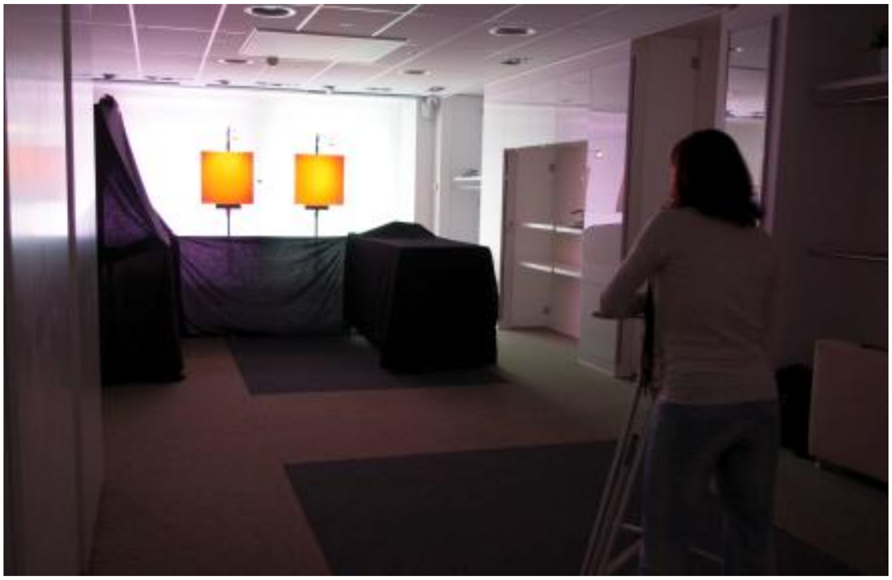


Figure 4.3. Experiment room.

4.2.3. Procedure

At the beginning of the experiment, each participant took Ishihara's color blindness test and the visual acuity test. The ones who had vision deficiencies were asked to take the test with their correction equipments. After that, different types of experimenting techniques were tried in order to find the right way to measure the depth perception differences of the colors. According to that, some pilot tests were conducted and a forced choice paired comparison test appeared to be the main method to find out if colors and different color combinations have any effect on distance perception.

4.2.3.1. Pilot Studies

Before continuing with the forced choice method for the experiment, there were different designs of method tested as pilot studies. At first, a tuning method starting from equal distances of two objects was conducted. In the method, the left object stayed stable and the right object was moved to the front or the back according to the participants' instructions. However, in this method no difference was perceived by the participants. As the second method, a two-way tuning starting from different positions of two objects was conducted. In this method, while the right object stayed stable, the left object was moved from the front to the back and from the back to the front according to the participants' instructions in order to equalize the distances of the two objects from the point of view of the participants. After the participation of two subjects, varied results were obtained depending on the subjects, and this turned out to be a hard experiment for the participants to follow and respond.

Due to the varying results of each participant, it was decided that the baselines for each participant should be measured. In baseline measurements, cool white background with two objects in the same color were judged by the participants. Hence, no differences between objects and the background of these objects; in other words no perceived differences between them were expected. However, each participant perceived varying differences between the distances of two objects; for this reason, a baseline measurement was necessary for each participant in order to specify their zero point. Consequently, a two-way tuning method with baseline measurement was conducted. In this method, random repetitions of front-back and back-front of the objects displayed once again and large variations between baselines of different participants were obtained. Since the two-way tuning method was hard for participants to manage, a paired comparison test was found suitable to be applied with baseline measurements. Due to the statistical method that was going to be used (Monte Carlo method with psychometric curves), the paired comparison test was done in forced choice method. In forced choice method, "[…] the influence of varying observer criteria on the results" can be eliminated (Fairchild, 2005, p. 44).

4.2.3.2. Forced Choice Paired Comparison Test

The experiment is completed in two phases in which the first one leads to the second phase in order to have more reliable and valid data to consider the hue differences and background-object combinations.

4.2.3.2.1. First Phase

At the beginning, thirty five combinations of stimulus with colored lit background pairs and two same colored objects which were created with 6 light colors and 3 object colors were judged by thirty five participants. Each participant evaluated 2 cases; one with cool white background and the second one with one of the combinations shown in Table 4.3.

Table 4.3. 35 combinations of object and background colors.

	Object color	Colored Background Pair	
1	orange object	warm white light	blue light
2	orange object	warm white light	green light
3	orange object	warm white light	red light
4	orange object	warm white light	cool white light
5	orange object	cool white light	blue light
6	orange object	cool white light	green light
7	orange object	cool white light	red light
8	orange object	blue light	green light
9	orange object	blue light	red light
10	orange object	red light	green light
11	blue object	warm white light	orange light
12	blue object	warm white light	green light
13	blue object	warm white light	red light
14	blue object	warm white light	cool white light
15	blue object	cool white light	orange light
16	blue object	cool white light	green light
17	blue object	cool white light	red light
18	blue object	orange light	green light
19	blue object	orange light	red light
20	blue object	red light	green light
21	gray object	warm white light	blue light
22	gray object	warm white light	orange light
23	gray object	warm white light	green light
24	gray object	warm white light	red light
25	gray object	warm white light	cool white light
26	gray object	cool white light	blue light
27	gray object	cool white light	orange light
28	gray object	cool white light	green light
29	gray object	cool white light	red light
30	gray object	orange light	blue light
31	gray object	orange light	green light
32	gray object	orange light	red light
33	gray object	blue light	green light
34	gray object	blue light	red light
35	gray object	red light	green light

As it was already learned from the pilot studies that even the baselines of the participants vary the one with cool white background was taken as the baseline for each participant to compare the perceived distance difference between the colored pairs. For each participant, one of the three colored objects (orange, blue or gray) was presented in front of the lit backgrounds. For two cases of background color, the object colors were kept constant for each participant. Thus, for each participant only the background color changed in order to evaluate the absolute distance and understand if color changes on a wall will make any difference on distance perception. In the color combinations, same colors both on the object and in the background were never used (orange object sets did not include orange light as a background and blue object sets did not include blue light as a background).

During the experiment, the left object stood stable; however, the right object moved back and forth according to the previously defined distances, and participants were asked to compare the distances of two objects according to the point where they were standing and tell which object (right or left) they perceived in the front. Seven points with 10 cm differences were defined to place the left object. The six points were 30 cm, 20 cm and 10 cm in front of the right object and 30 cm, 20 cm and 10 cm back of the right object, and the seventh point was 0 cm where the two objects were at an equal distance to the viewer. Each point was presented 10 times randomly during the experiment, which made 70 points for each background. As each participant evaluated two backgrounds, 140 points in total were judged by one participant (see Appendix A for an example of data recording). In order to hide where the object was moved by the experimenter, participants were asked to close their eyes while the place of the left object was being altered.

In addition, the experiment was conducted monocularly to avoid the effects of binocular cues and to make sure that the obtained distance differences were derived because of color only. The participants took the dominant eye test and they took the experiment with their dominant eye. In addition, depending on the participants' speed of evaluating, the experiment took 20-35 minutes.

4.2.3.2.2. Second Phase

For the second phase of the experiment, 21 participants who were consistent with their answers in the first phase were chosen. However, two of these participants had already left the company, so the experiments were conducted with 19 of them. This phase of the experiment was for increasing the number of participants for the background colored pairs. However, since the number of cases that had been planned to be tested was excessive to be managed with more participants, and the experiments for each participant took more than 20 minutes, the cases of color combinations were narrowed. In order to test different hue effects on depth perception, each hue was displayed with cool white as a pair at the background. As a result, the pairs for background were chosen as cool white-orange, cool white-blue, cool white-green, cool white-red and warm white-cool white. Besides, according to the obtained results from the previous phase, there were some similarities between red, green and orange, blue colors, in order to compare them directly with each other, red-green and orange-blue pairs were also tested in the second phase. All of those seven background pairs were displayed with the same three colored objects (orange, blue and gray) which had already been used in the first phase. Therefore, in total 17 combinations with three object colors and seven background lit pairs were evaluated (see Table 4.4.). The method was kept the same as that in the first phase.

Table 4.4. Color combinations evaluated in the second phase.

	Object color	Colored Background Pair	
1	orange object	warm white light	cool white light
2	orange object	cool white light	blue light
3	orange object	cool white light	green light
4	orange object	cool white light	red light
5	orange object	red light	green light
6	blue object	warm white light	cool white light
7	blue object	cool white light	orange light
8	blue object	cool white light	green light
9	blue object	cool white light	red light
10	blue object	red light	green light
11	gray object	warm white light	cool white light
12	gray object	cool white light	blue light
13	gray object	cool white light	orange light
14	gray object	cool white light	green light
15	gray object	cool white light	red light
16	gray object	red light	green light
17	gray object	orange light	blue light

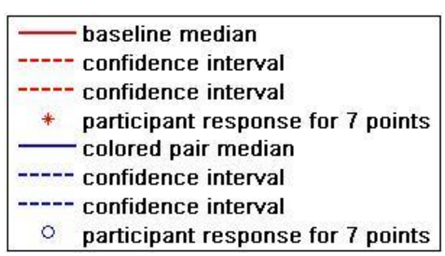
If the participants took the previous experiment with the gray object, then they again evaluated the gray object in the second phase. By means of this, since we already had their baselines with the cool white background in the first phase, the second phase was directly conducted with the colored pairs at the background. At the end, each color combination was evaluated by three participants.

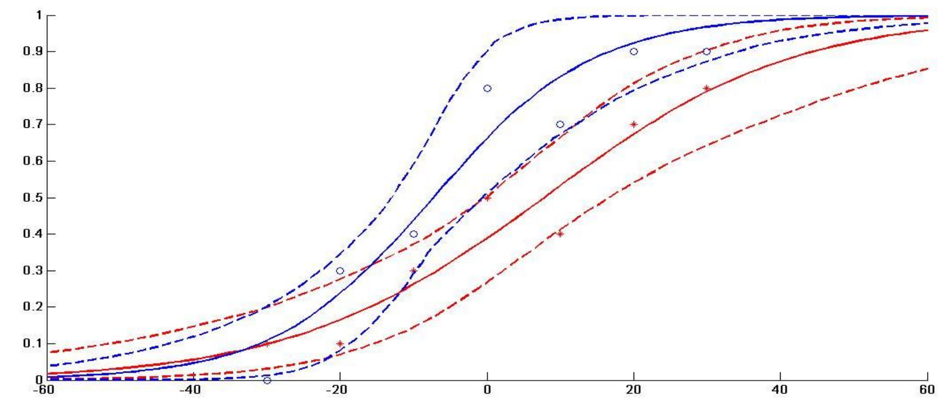
4.3. Findings

For the experiment, Monte Carlo by resampling the psychometric curves with bootstrapping and ANOVA were used as the statistical methods. In the experiment many different methods were conducted and forced choice pair comparison test was found to be the most suitable one. According to the forced choice paired comparison test, the responses of the participants indicating whether the right or left object is perceived nearer were taken as the data for psychometric curves. Due to this data (the responses of 10 times repeating 7 different distance points), either 0 (right object perceived nearer) or 1 (right object perceived farther) values for curve ranges were obtained on x-axis to the psychometric curves for both the baseline and the background pairs for each participant for each color combination. In order to create a model and to do a proper statistical analysis, the fitted curves for each color combination for a single participant were resampled 1000 times using the bootstrapping technique to obtain confidence intervals and more accurate median lines with more valid results. According to the confidence intervals, median curves of both the baseline and background pair were obtained (see Appendix B and C). After that, the difference between two median curves (baseline and background pair curves) from the confidence intervals of 0.5 point threshold was calculated, and with Monte Carlo method the significances of the color differences for each participant was estimated. After that, in order to check the overall results of the participants, the differences calculated from 0.5 point thresholds for each participant were used as dependent variable in ANOVA test (see Appendix D).

ANOVA was run on the complete set of data, with the difference between medians of baseline and background pairs of each participant as the dependent variable, and object color (orange, blue, gray) and background pair (cool white-blue, cool white-green, cool white-red, cool white-orange, warm white-cool white, red-green, orange-blue) as the independent variables. Results showed that different object colors significantly affected perception of distance, $F(2,34) = 13.83$, $p < 0.001$. Hochberg's GT2 test revealed that there were different depth perceptions occurring between orange and the other two colors (blue and gray) (see Appendix D). Besides, the mentioned results from ANOVA and Hochberg's GT2 tests, there were also obtained p-values from Monte Carlo tests for psychometric curves. All the p-values that are going to be mentioned in this chapter for psychometric curves are the results of Monte Carlo test. According to that, psychometric curves confirmed that there was a distance difference between object colors, especially with cool white-green background pair. According to all three participants who evaluated cool white-green background pair with orange and blue objects, there were no distance differences; however, when the same background pair with gray objects was judged, all three participants perceived differences ($p=0.008$, $p= 0.008$, $p= 0.001$) (see Figure 4.5).

Examine all the psychometric curves according to;

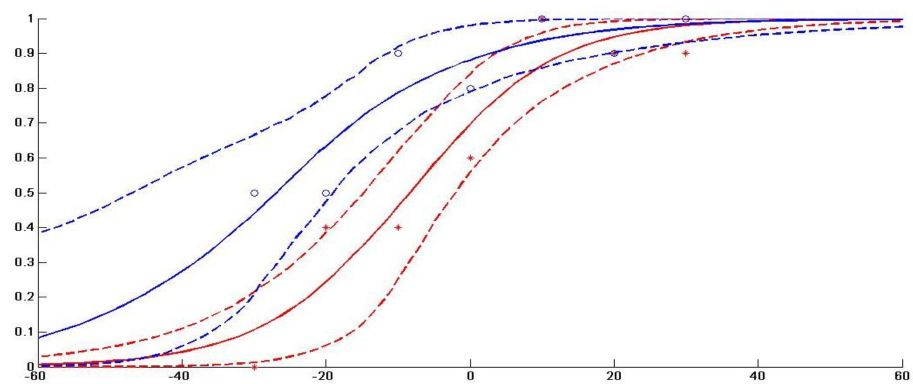




Gray object

Cool white – Green background

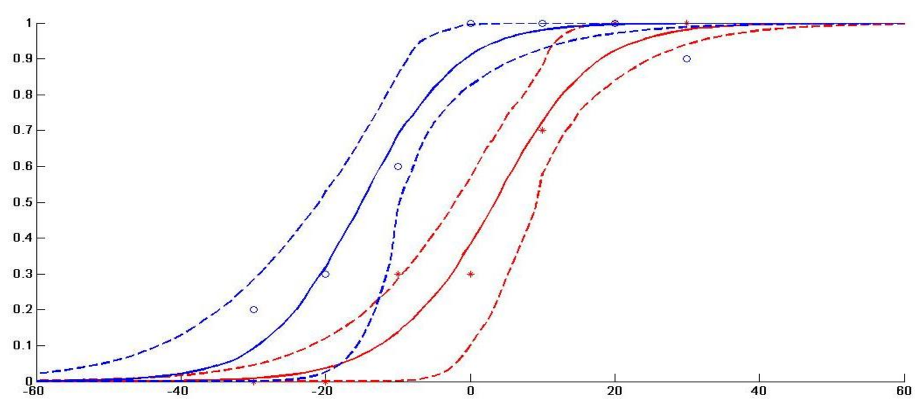
Difference: 15.14 cm



Gray object

Cool white – Green background

Difference: 18.76 cm



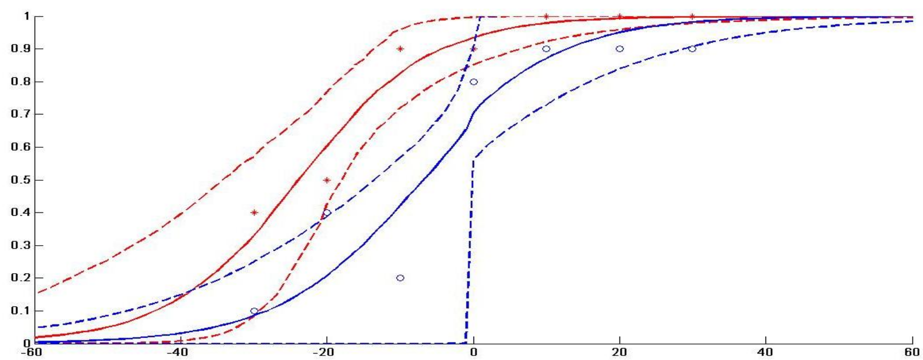
Gray object

Cool white – Green background

Difference: 18.56 cm

Figure 4.5 Psychometric curves for three participants which are represented one by one with baseline and background pair measurements.

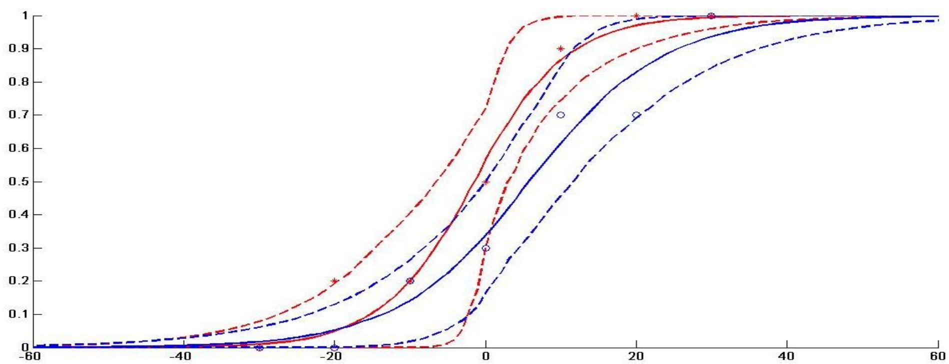
From the psychometric curves, it can be understood that there is a tendency to perceive the gray object nearer in front of the green background than the cool white background. If cool white-blue background pair was discussed according to the object colors in front of it, then all three participants perceived distance differences with orange objects ($p= 0.003$, $p= 0.044$, $p= 0.042$) (see Figure 4.6).



Orange object

Cool white – Blue background

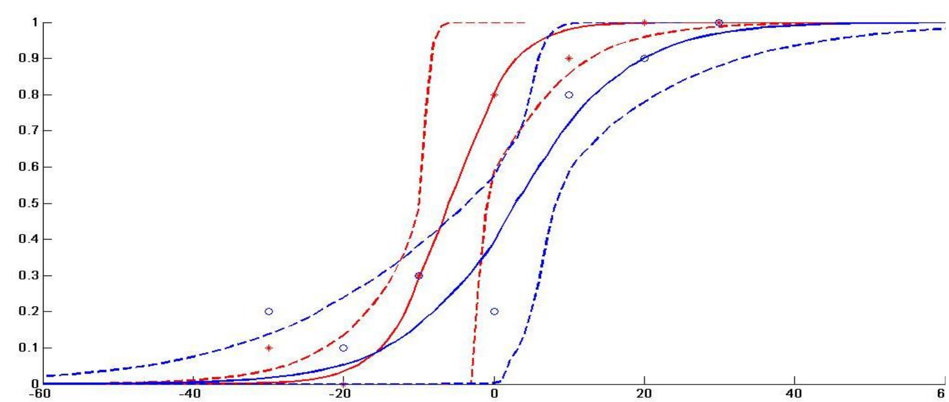
Difference: -17.68 cm



Orange object

Cool white – Blue background

Difference: -7.36 cm



Orange object

Cool white – Blue background

Difference: -8.85 cm

Figure 4.6. Psychometric curves for three participants which are represented one by one with baseline and background pair measurements.

According to the psychometric curves, orange object appeared nearer with approximately 12 cm difference in front of cool white background than blue. Contrarily, just one of the participants perceived distance difference between cool white and blue background colors when they were displayed with the gray object, and according to that participant the gray object appeared nearer with 10 cm difference in front of blue instead of cool white (p= 0.005) (see Figure 4.7).

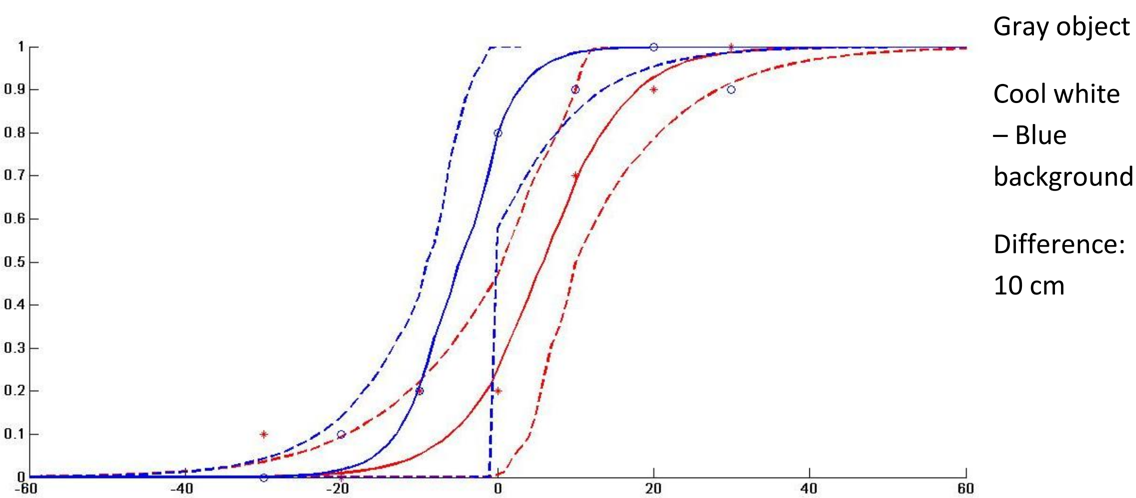
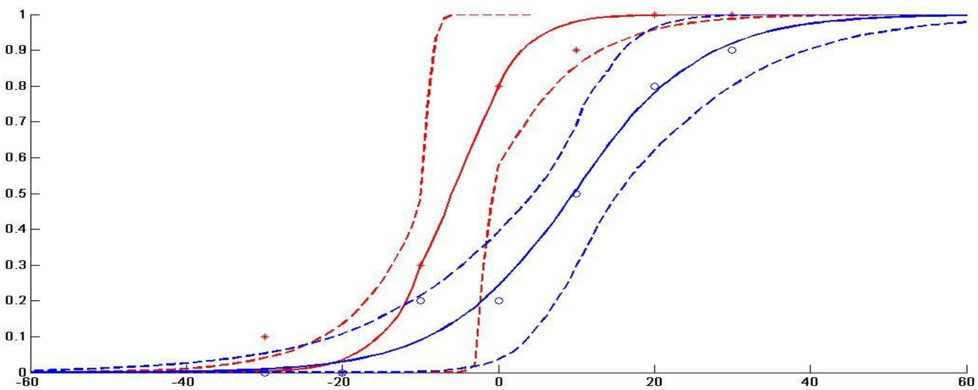


Figure 4.7. Psychometric curve for one participant with baseline and background pair measurements.

Additionally, with red-green background for all three object colors, there was one result which reveals a distance difference for each object from three participants according to psychometric curves. For blue (p= 0.003) and gray (p= 0.001) objects, the objects in front of green background reflected a tendency to be perceived nearer than the one in front of red background. Besides, the difference between colors was 10 cm with blue object, and it doubled with the gray object. On the contrary, for the orange object, the one in front of the red background had the tendency to be perceived nearer than that in front of the green background with a difference of 10 cm ($p= 0.022$). Furthermore, when cool white-orange background was considered, there were no differences obtained for blue object except for just one participant for the gray object ($p= 0.020$) where the object in front of cool white background was perceived 10 cm nearer than it was in the orange background (see Appendix C).

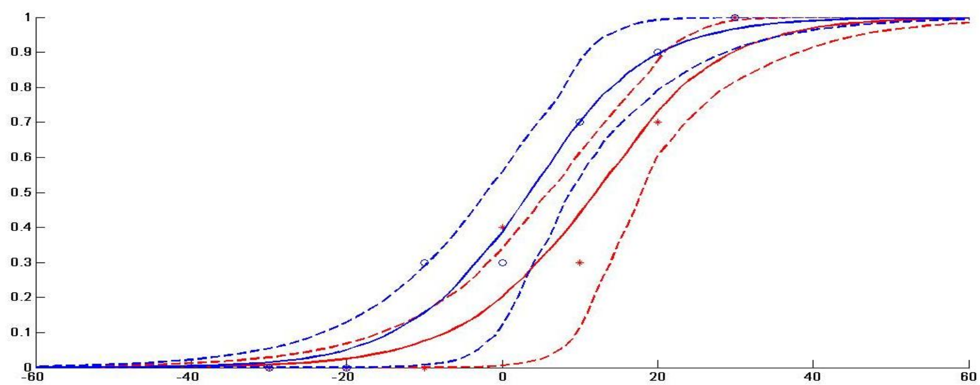
Moreover, in order to understand if color temperature makes any difference in depth perception depending on the object color in front of it, warm white-cool white background pair was evaluated for three object hues. According to the psychometric curves, depth perception difference between warm white and cool white background can be mentioned for orange and blue objects; however, there was no distance difference for the gray object. According to Monte Carlo tests, p-values for the orange object from one participant ($p< 0.001$) and blue object from two participants ($p= 0.042$, $p= 0.003$) denoted that the blue object had a tendency to be perceived nearer in front of warm white background, where the orange object had a tendency to be perceived nearer in front of cool white background. The perceived difference for warm white and cool white background was 15 cm for the orange object and approximately 10 cm for the blue object (see Figure 4.8).



Orange object

Warm white – Cool white background

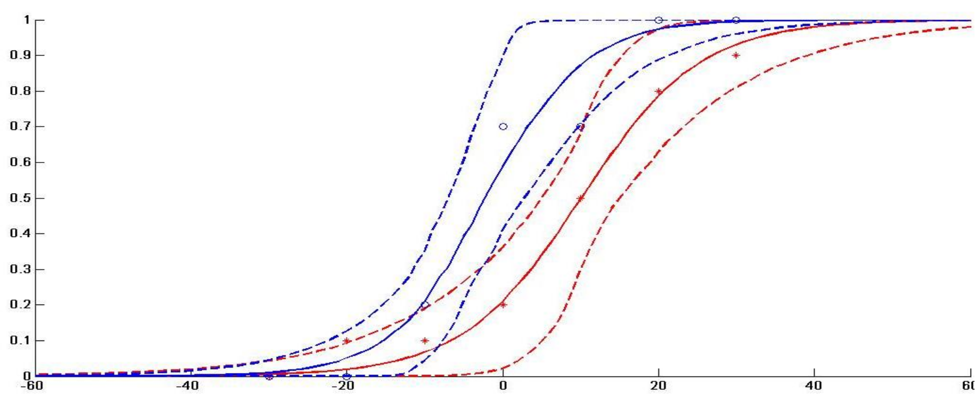
Difference: -15.48 cm



Blue object

Warm white – Cool white background

Difference: 8.61 cm



Blue object

Warm white – Cool white background

Difference: 12.27 cm

Figure 4.8. Psychometric curves for three participants which are represented one by one with baseline and background pair measurements.

Additionally, the results of ANOVA showed that there was a significant difference between background hue pairs, $F(6, 34) = 2.433$, $p= 0.046$ and according to the results, there were no significant interaction effects of object color and background color pairs. However, Hochberg's GT2 test revealed that there was a difference between cool white-blue and orange-blue pairs. Besides, there were some differences between background hue pairs, which can be mentioned qualitatively with reference to Monte Carlo tests of the psychometric curves. The interaction effects of colors with background lit pairs can be seen in Appendix D.

If background sets with the orange object are considered, the effect of cool white-red background pair was accurate for just one participant ($p= 0.015$). Also, according to the difference, the orange object in front of a red background was perceived nearer than it was in cool white background. Similarly, there were no distance differences observed for the cool white-green background pair. Although, green didn't show any difference when displayed with cool white, there was an effect of it when displayed as red-green pair. For one of the participants, orange object in front of the red background had the tendency to be perceived nearer than it was in front of the green background with 10 cm difference ($p= 0.022$) (see Appendix C and E).

In the sets of blue object, there were no distance differences obtained with the cool white-green and cool white-orange background pairs. Two participants perceived distance difference between cool white and red backgrounds ($p= 0.026$). According to the psychometric curves, the blue object in front of the red background had the tendency to be perceived nearer than it was in front of the cool white background with approximately 15 cm difference. Besides, one participant perceived distance difference between the red and green backgrounds ($p= 0.003$) in which the blue object in front of the green background was perceived 10 cm nearer than it was in the red background (see Appendix C and E).

With the sets of gray object, similar effects of cool white-blue, cool white-green, cool white-red and cool white-orange pairs on distance perception were observed in the psychometric curves. In all of those cases, if there was a difference between the median curves of the participants, these differences indicated that the object in front of the colored backgrounds had a tendency to be perceived nearer than it was in front of the cool white background (see Appendix C, and E for the plots, their p-values and perceived differences between the colored background pairs). For cool white-green pair, this difference was accurate for all three participants and the difference perceived between cool white and green hues was approximately 18 cm ($p= 0.008$, $p= 0.008$, $p< 0.001$). This pair had the biggest difference and cool white-red pair follows cool white-green pair with the approximate distance difference of 15 cm, but in this case, the results of two participants were accurate ($p= 0.001$, $p= 0.005$) instead of three. Besides these, for both cool white-blue ($p= 0.005$) and cool white-orange ($p= 0.020$) pairs, there was one accurate result obtained for each background pair from three participants. According to these results, both hues indicated approximately 10 cm difference from cool white background. In this manner, distance differences with green and red backgrounds were more accurate than the distance differences with blue and orange backgrounds compared with cool white due to higher distance differences.

In addition, however, there were similar results for the pairs of cool white-blue and cool white-orange. When blue and orange hues were displayed together as a pair, distance difference was obtained for all three participants ($p= 0.026$, $p= 0.004$, $p= 0.008$). According to these results, the gray object in front of the blue background had a tendency to be perceived nearer than it was in the orange background with the approximate difference of 13 cm. On the other hand, when red and green hues were displayed as a pair, the distance difference was perceived by one participant ($p= 0.001$) instead of three or two as it was in cool white-green and cool white-red pairs, and the perceived difference was nearly the same in all three background conditions. For the summary of results according to the colored background pairs see Table 4.5.

Table 4.5. Presentation of which colored object was perceived nearer in front of which colored background and how many participant perceived difference for each background pair.

Colored Background Pair	Orange Object		Blue Object		Gray Object	
	Perceived nearer	Participant nb.	Perceived nearer	Participant nb.	Perceived nearer	Participant nb.
Cool white-blue	Cool white	3	_____	_____	Blue	1
Cool white-green	_____	0	_____	0	Green	3
Cool white-red	Red	1	Red	2	Red	2
Cool white-orange	_____	_____	_____	0	Orange	1
Warm white-cool white	Warm white	1	Cool white	2	_____	0
Red-green	Red	1	Green	2	Green	1
Orange-blue	_____	_____	_____	_____	Blue	3

5. DISCUSSION

In this study, the effects of different colors and different color combinations on depth perception in interior spaces were studied. It was hypothesized that there are different depth perceptions according to the background hue and its combination with objects which has different hues. Another hypothesis was that there are differences in depth perception depending on the color temperature of background lit and object hue in front of it. The differences in the perception were analyzed depending on object color and background color.

The results showed some similarities and differences with the literature. When object colors were analyzed, blue and gray colored objects were found to have similar tendencies in differences, where the orange object generally showed opposite results, which verifies the hypothesis of the study. Blue and gray colors are cooler than the orange object and they were generally perceived farther than the orange one, which shows a similarity to the study carried out by Bailey et. al. (2006). According to their (2006) study, warmer colored objects appeared closer than cooler ones. Besides that, mainly there were bigger differences observed with the gray object than the blue or orange object. Mount et. al. (1956) mentioned that “each color was seen in front of its nearest matching gray” (p.210). In this study, it is revealed that blue and orange were generally perceived nearer than gray, which had the nearest brightness matching with the other two colors.

Another similarity with the literature can be mentioned about red and blue combinations. According to the literature, due to chromatic aberration “red and blue showed especially striking differences” (Pillsbury and Schaffer, 1937, p. 126). In this study, when blue object sets were analyzed, the biggest difference was obtained with cool white-red background pair. Besides, for the orange object, the biggest difference was also perceived with cool white-blue background pair.

Contrary to the information in the literature which claims that short-wavelength colors appear nearer than long-wavelength colors, the results of this study doesn’t follow the same order. Instead of warm and cool colors theory, it is possible to mention the effect of opponent-colors theory (Fairchild, 2005). According to the theory, there is a fundamental phenomenon about red-green and yellow-blue pairs in terms of color receptors in the brain. Cone signals allow construction of red-green (L-M+S channels) and yellow-blue (L+M+S channels) opponent signals (Fairchild, 2005). When gray object sets were analyzed in order to find out about background color effect, cool white-red and cool white-green backgrounds had similar differences in the same direction, as cool white-blue and cool white-orange background pairs had similar effect. With cool white-blue and cool white-orange pairs the difference was half as much as it was in cool white-red and cool white-green pairs. Moreover, for all of the background pairs, the object in front of the colored backgrounds was perceived nearer than it was in cool white background. Furthermore, when red-green background pair was evaluated, it, however, changed according to the participant, so no big differences were obtained. Besides, when orange-blue background pair was evaluated there was a significant difference. In that case, it is possible to say that different background combinations also have an effect on depth perception. Additionally, for background color combinations, there was no effect of color temperature on depth perception when it was judged with gray object; however, depending on object color, it showed differences in different directions.

As a limitation of the study, due to the baseline and estimation of the distance variations between participants, a method which had specific measuring points and repetitions were applied. Therefore, each participant took a longer experimental period than expected. Hence, three participants for each color combination could be taken to the experiment and because of the variations between them it was not suitable to evaluate all of the data obtained from all of the participants regardless of the confidence intervals. Consequently, to explore the effects of color on depth perception, the results obtained from the psychometric curves of participants were also interpreted one by one. In future studies, to standardize the baseline factor and to provide the perceived distance difference, a starting point for the previously specified 7 points can be determined according to the baselines of each participant instead of keeping it stable for each participant. In other words, if a participant has a deviation of 10 cm, the starting point can be taken as 10 cm instead of 0 cm and the distances can be specified as 20, 30 and 40 instead of 10, 20 and 30.

6. CONCLUSION

The effects of color and its combination with colors of the background light on depth perception in interior spaces were investigated in an experiment which had two parts depending on the participants’ contribution to the test. The results of the statistical study showed significant effects of color and colored light on depth perception in terms of different baselines and distance perception of participants.

As indicated in the literature review, different cues of depth have been studied including object color and light color effects with small colored chips and mock-up designs (Mount et. al., 1956; Bailey et. al., 2006; Ichihara et. al., 2007; Huang, 2007). Besides, all of them have generally examined brightness and saturation attributes of color and their influence on depth perception. There are no studies exploring hue effect on depth perception in 1/1 scaled interior spaces with the combination of object color and light color. The results of this research are important to fill the gap in the literature about color and colored light effects in interior spaces. It is observed that the effects of color and colored light on depth perception shows variations between participants.

The results of this study can be useful for interior architects, lighting and stage designers who need to create different depth perceptions in a space with object and background relations. In order to intentionally create the required atmosphere in the space, it is important for a designer to know the effect of color and light in a space. According to the study, the differences between hues are smaller than the variations in the baselines of the participants; because of that, these differences may not be applicable in the design field as it was expected. However, it is understood that as hue is found to have a small effect on depth perception with varying differences between participants, it is a less effective factor for depth perception than brightness effects which were obtained in other studies in the literature (Taylor and Sumner, 1945; Johns and Sumner, 1948; Mount et. al., 1956). Thus, designers may focus on brightness or saturation to obtain the desired effect of depth illusions more than hue.

Apart from the benefits of this study for the design field, the results can also be contributive to color science and human psychology studies concerning perception. Moreover, according to the experiences obtained from the longstanding method trials and implementations, it can also play an important role on how to generate the methods of experiments dealing with perception.

In future studies, if binocular viewing makes any difference on depth perception of colors and color lights in order to find out more practical usages and applications can be investigated. Besides, how colors and color combinations affect the room size can be looked into by making a contribution to this study in order to understand if the results obtained from depth perception tests are mostly influenced by the background or object colors. A more detailed research can be done in order to understand the reasons why the perception of participants showed so much variation with each other in the study.

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APPENDIX A

Table A.1 Sample data list for one participant from phase 2.

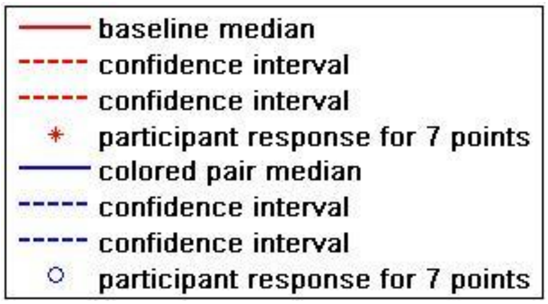
Participant 1/ Right Eye/ age: 25							
cw				cw-bl			
10	L	0	L	0	L	0	R
30	L	-30	R	20	L	-10	R
10	L	-10	R	20	L	-10	L
10	L	-30	R	30	L	-30	R
30	L	30	L	-20	L	20	L
-20	R	30	L	10	L	-20	R
-30	R	-20	L	0	L	-10	R
-10	L	-20	L	-30	R	10	L
-30	L	-10	L	0	L	30	L
-10	L	30	L	20	L	-30	R
-30	R	20	L	-30	R	10	L
0	L	10	L	30	L	-20	R
20	L	20	L	-10	R	10	L
30	L	-10	L	30	L	-20	R
-20	R	-30	R	-10	R	0	L
0	L	20	L	30	L	10	L
-10	L	-10	R	20	R	-20	L
-10	L	0	L	-30	R	-30	L
10	L	10	L	-20	R	20	L
-10	L	-10	R	10	R	30	L
-30	L	30	L	0	R	-10	R
20	R	-20	R	-20	R	30	L
-30	R	-20	R	10	L	-10	L
-20	L	0	L	-20	R	30	L
-20	L	10	L	10	L	-30	R
-20	L	20	L	-30	R	20	L
0	L	30	L	30	L	0	L
30	L	0	L	10	L	-30	R
20	L	10	L	-10	R	0	L
0	L	20	L	-20	L	10	L
10	L	10	L	20	L	-20	L
0	L	-30	R	-30	R	30	L
20	L	-20	R	-10	R	20	L
20	L	0	L	-10	R	20	L
30	L	-30	R	0	R	0	L

APPENDIX B

Table B.1 The list of color combinations and psychometric curves of Phase 1.

	Object Color	Colored Background Pairs	
1	orange	warm white light	blue light
2	orange	warm white light	green light
3	orange	warm white light	red light
4	orange	warm white light	cool white light
5	orange	cool white light	blue light
6	orange	cool white light	green light
7	orange	cool white light	red light
8	orange	blue light	green light
9	orange	blue light	red light
10	orange	red light	green light
11	blue	warm white light	orange light
12	blue	warm white light	green light
13	blue	warm white light	red light
14	blue	warm white light	cool white light
15	blue	cool white light	orange light
16	blue	cool white light	green light
17	blue	cool white light	red light
18	blue	orange light	green light
19	blue	orange light	red light
20	Blue	red light	green light
21	gray	warm white light	blue light
22	gray	warm white light	orange light
23	gray	warm white light	green light
24	gray	warm white light	red light
25	gray	warm white light	cool white light
26	gray	cool white light	blue light
27	gray	cool white light	orange light
28	gray	cool white light	green light
29	gray	cool white light	red light
30	gray	orange light	blue light
31	gray	orange light	green light
32	gray	orange light	red light
33	Gray	blue light	green light
34	gray	blue light	red light
35	gray	red light	green light

Figure B.1 Psychometric curves for the combinations (Follow according to Table B.1).



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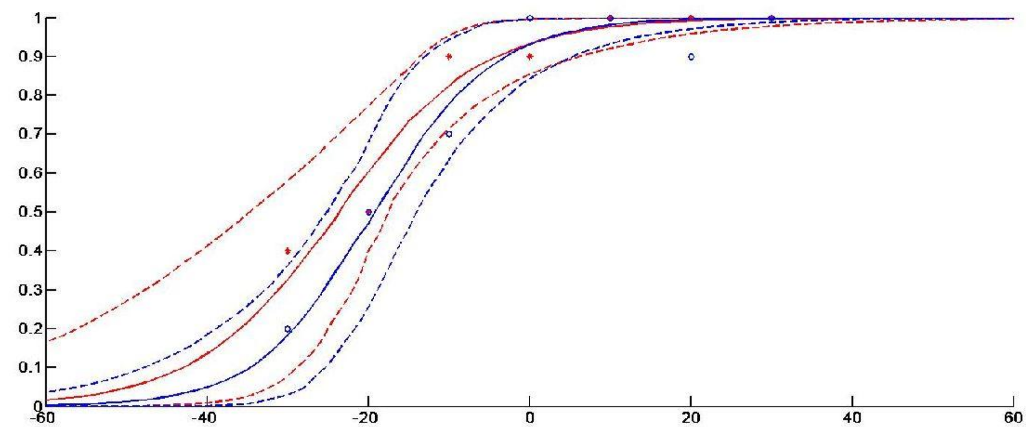

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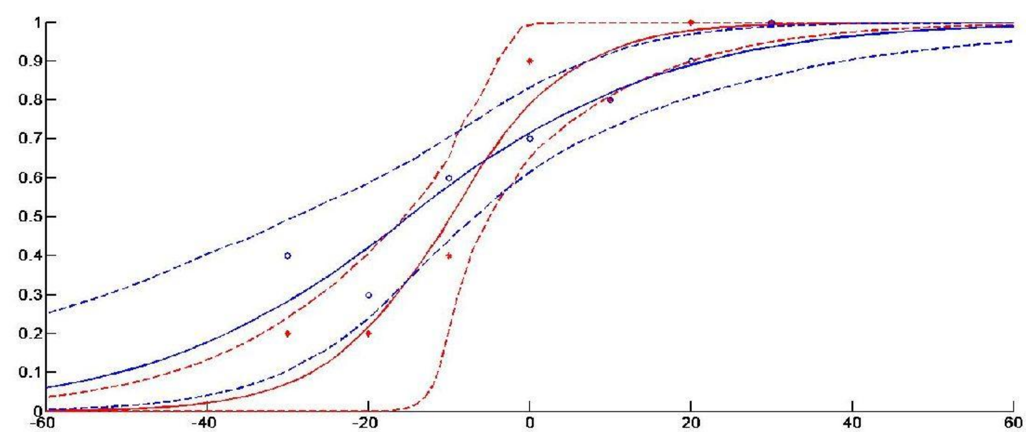

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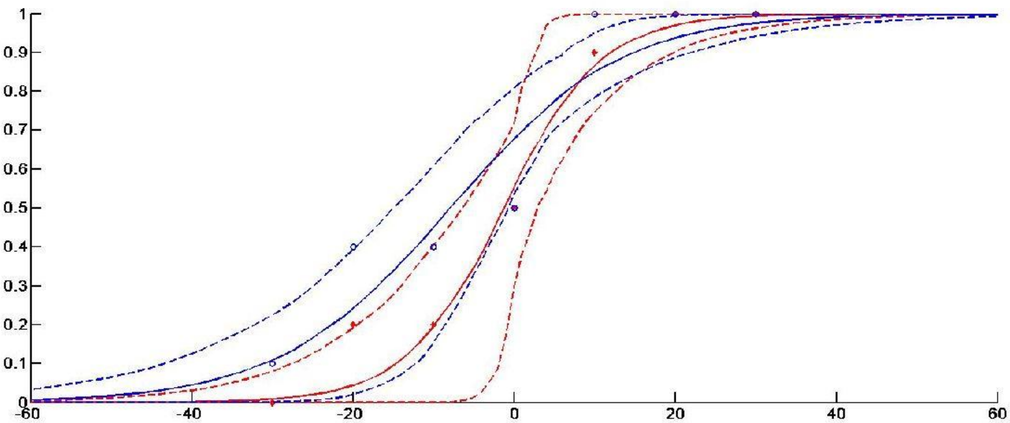

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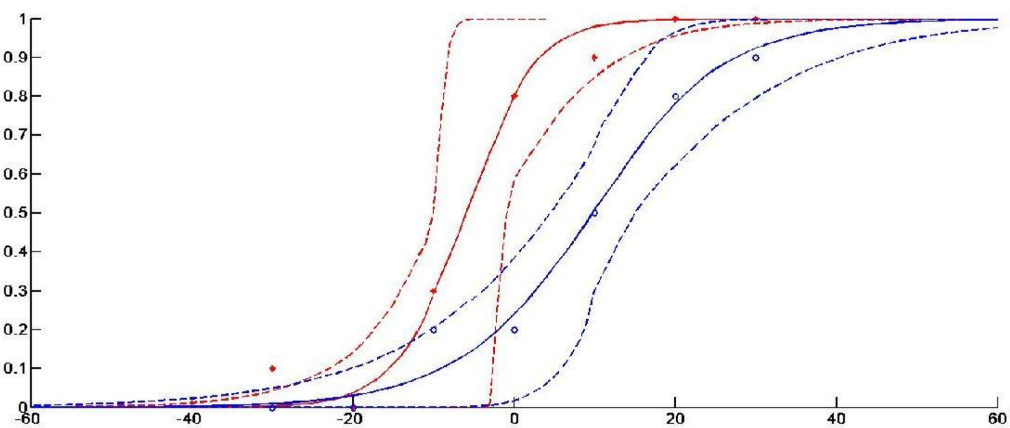

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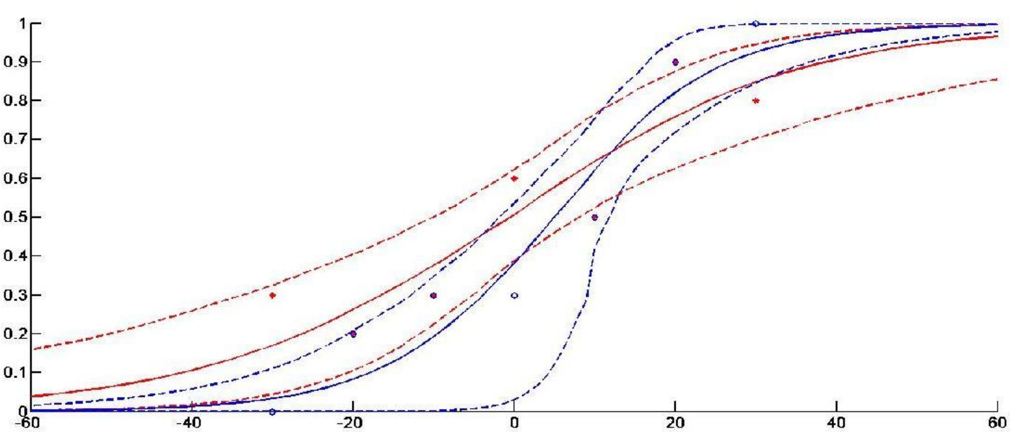

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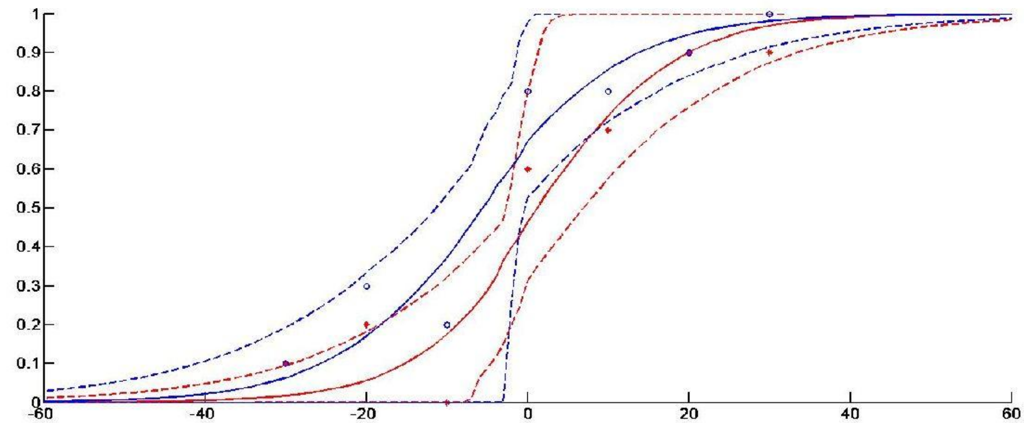
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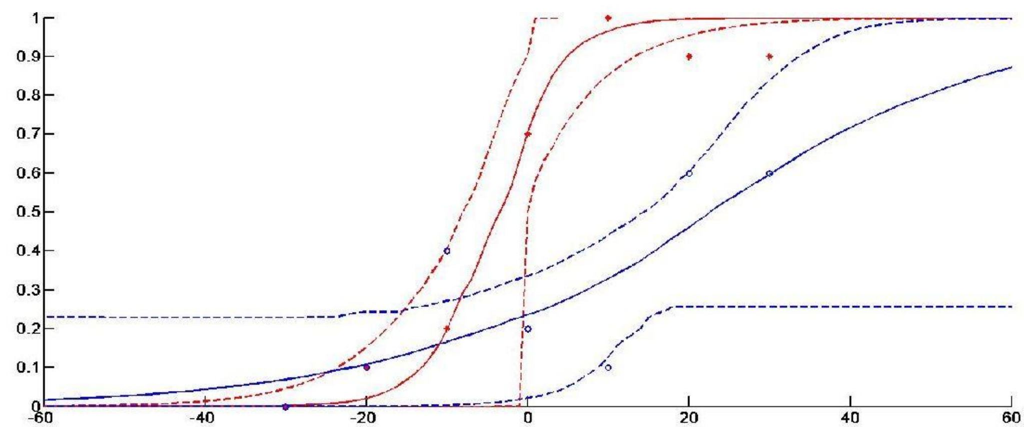
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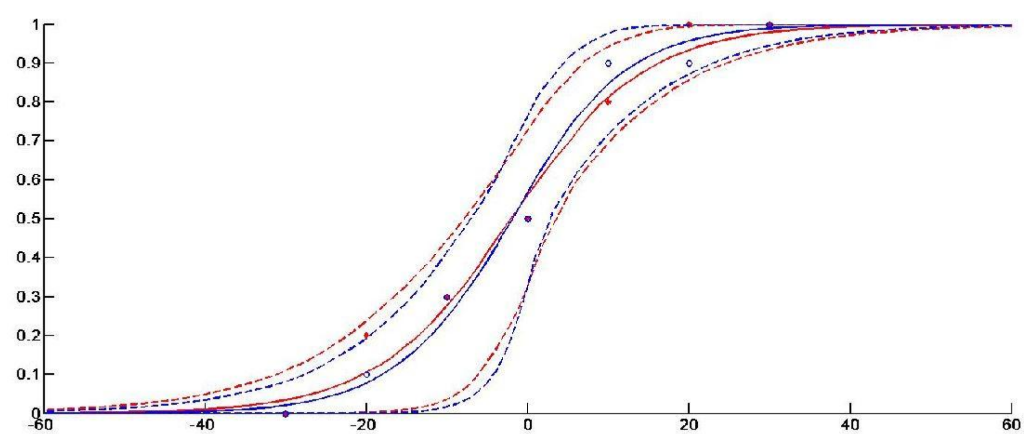
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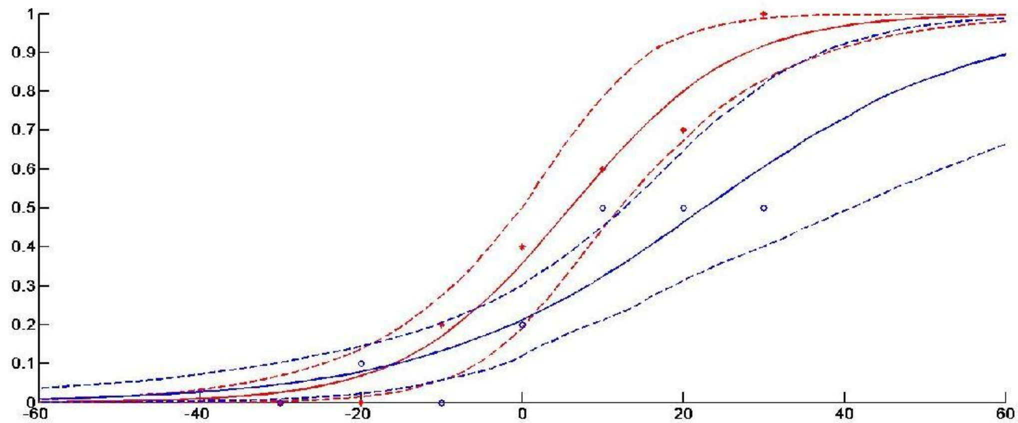
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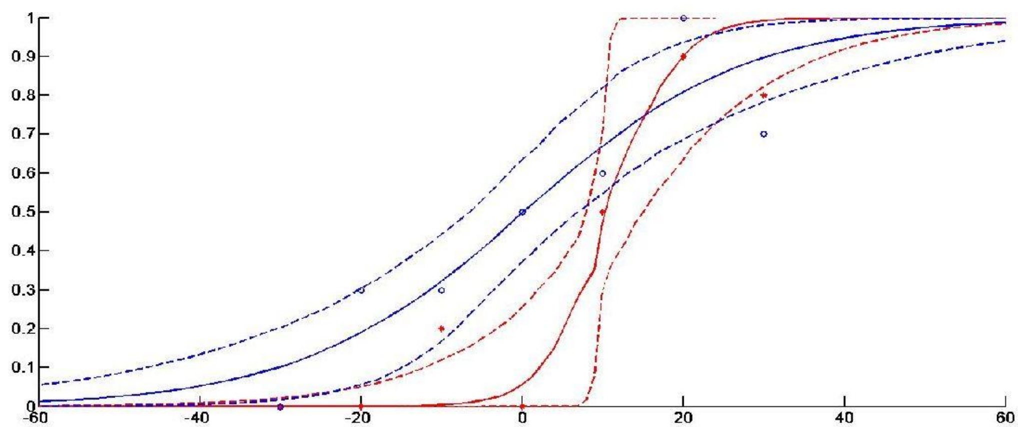
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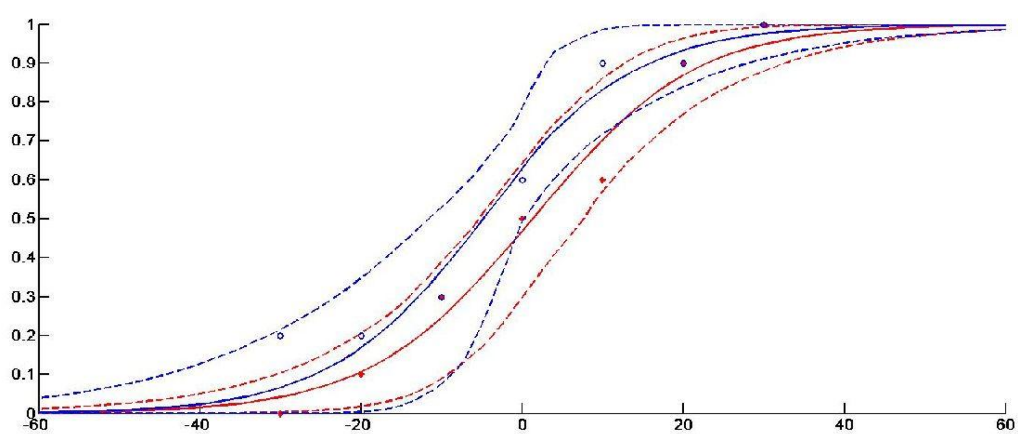
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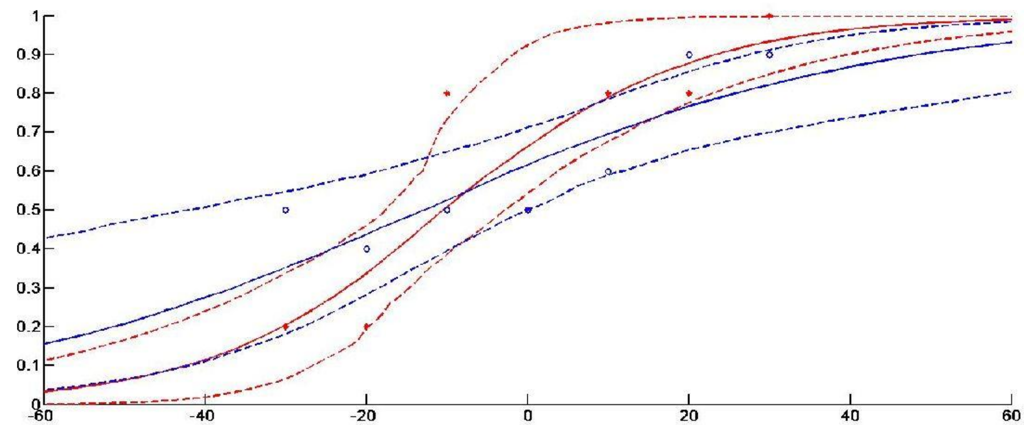
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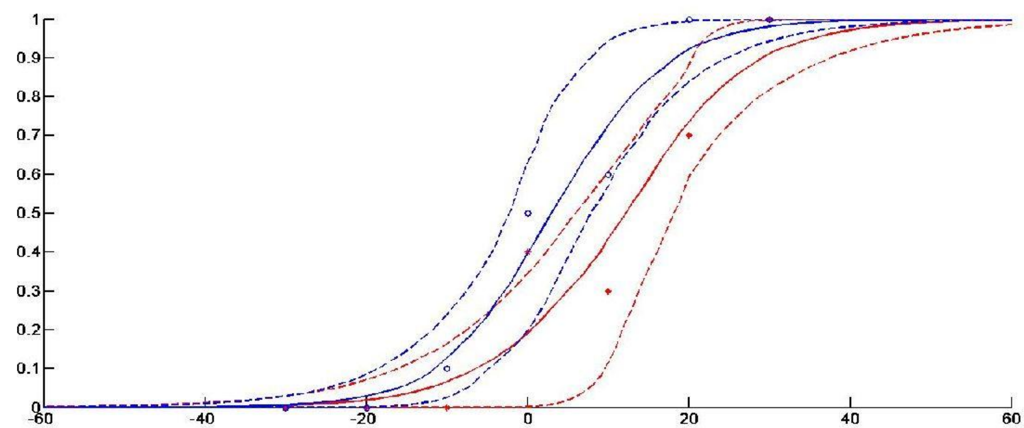
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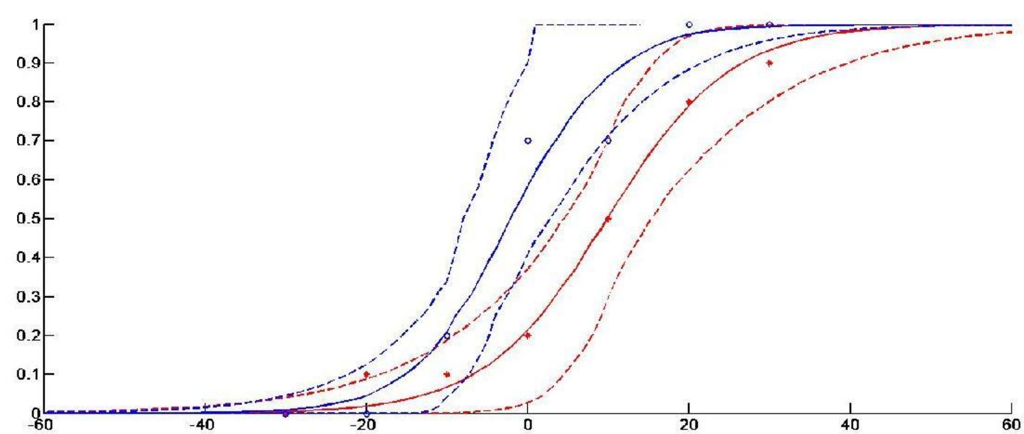
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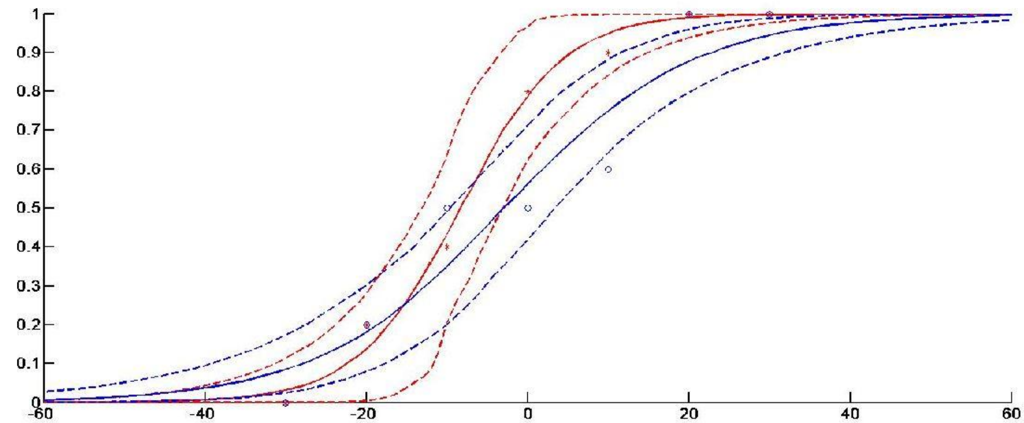

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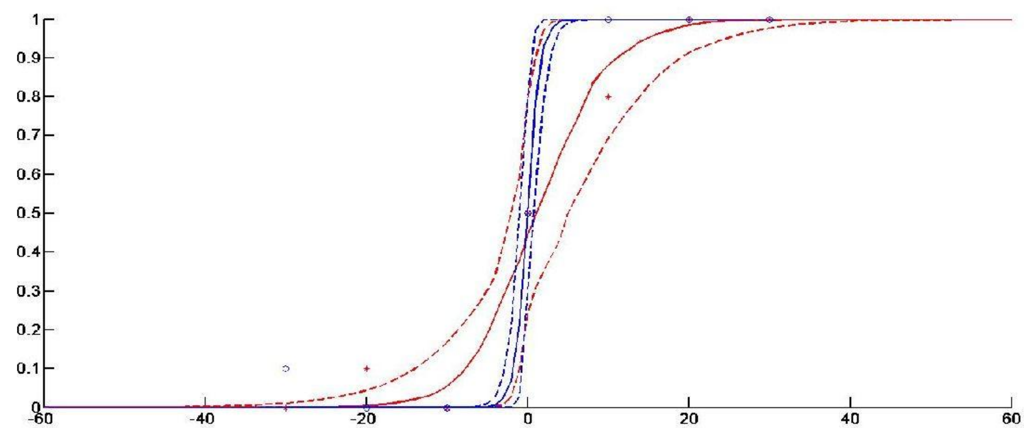

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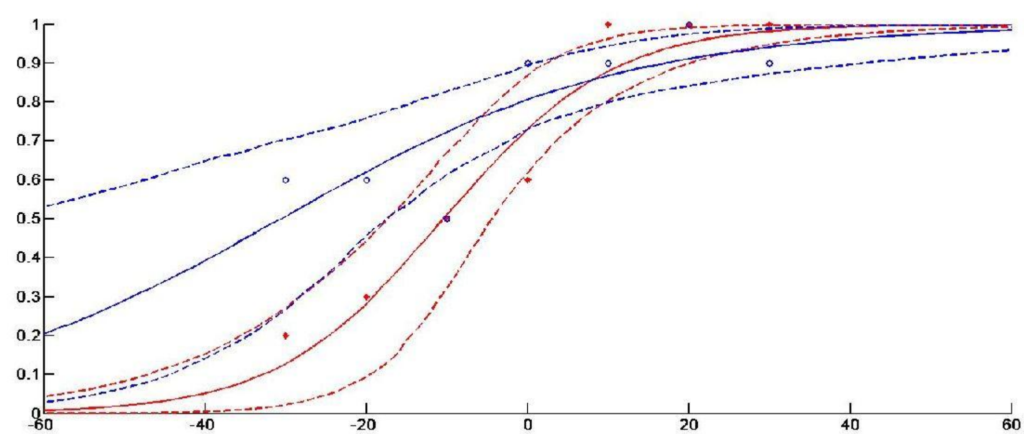

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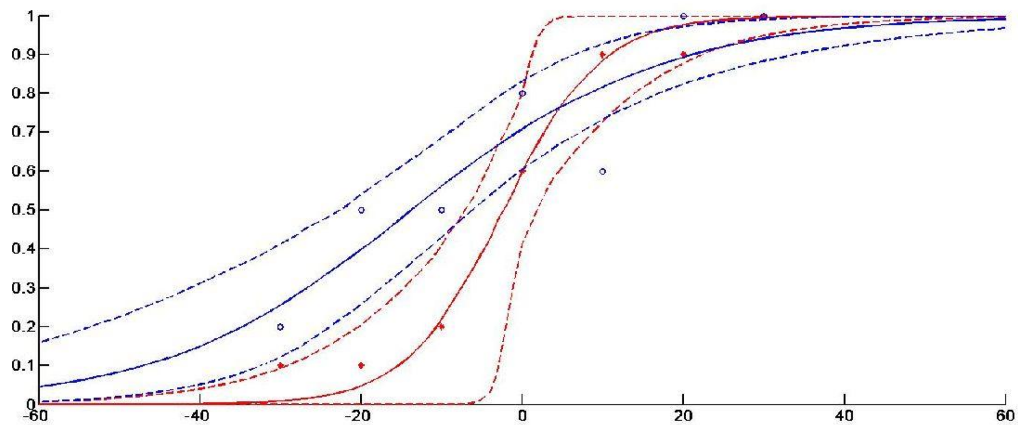
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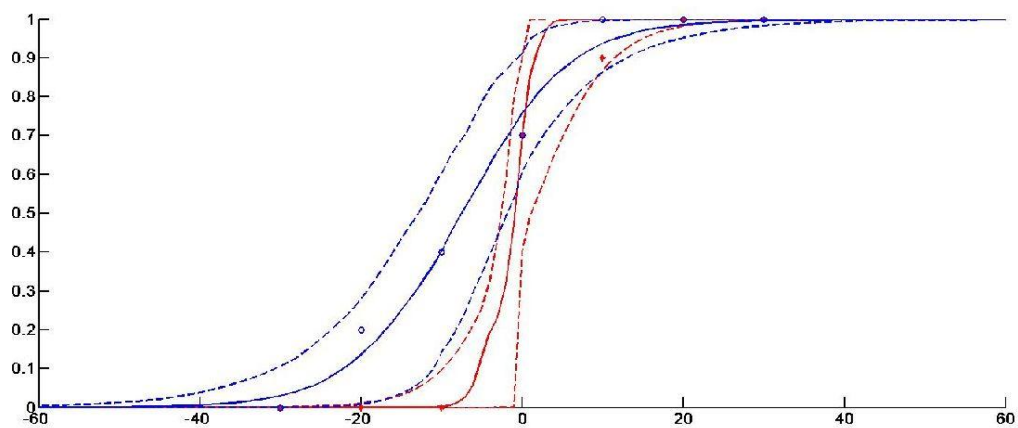
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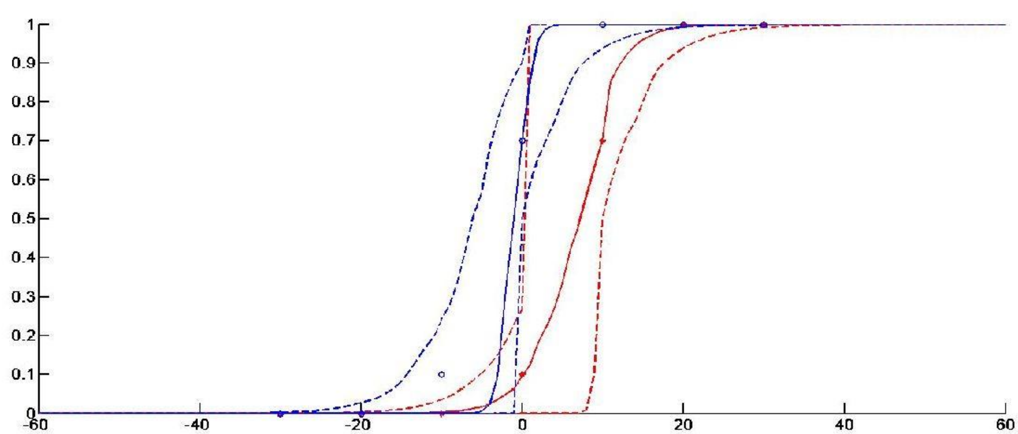
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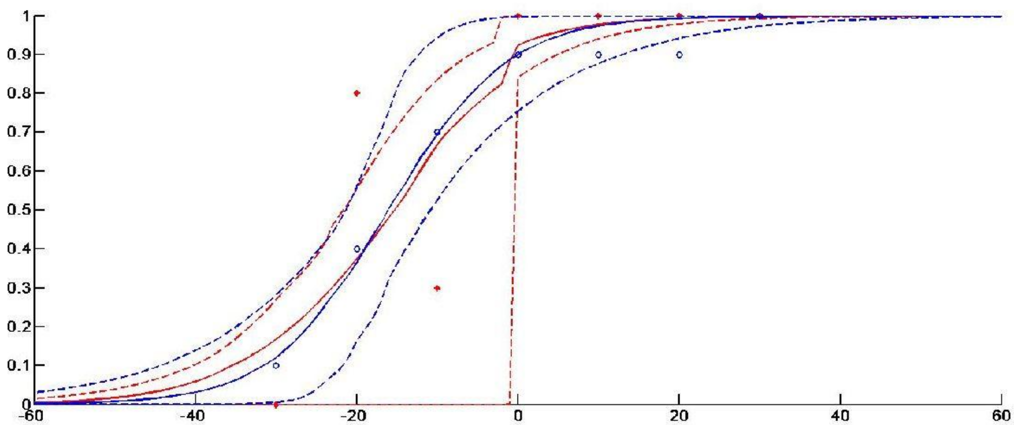
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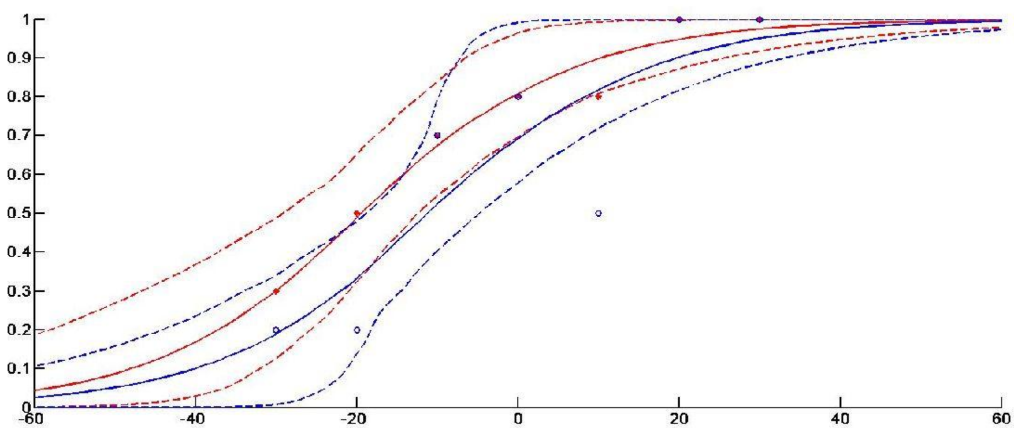
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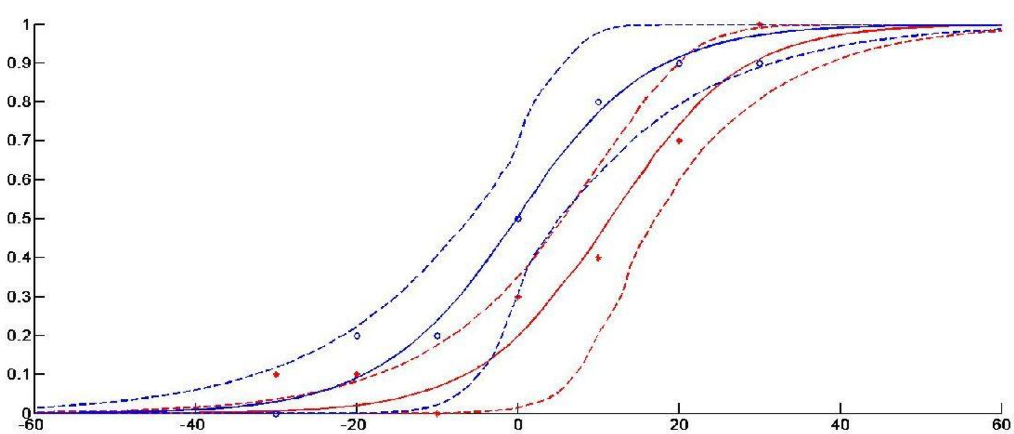
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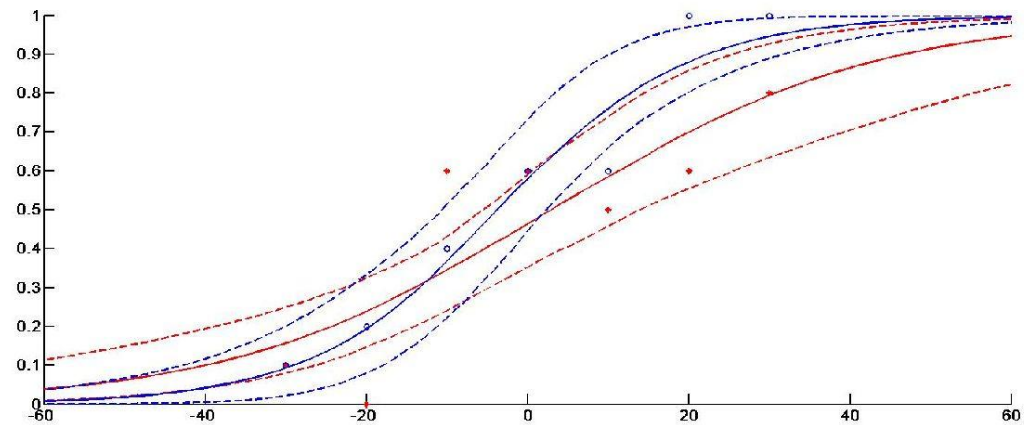

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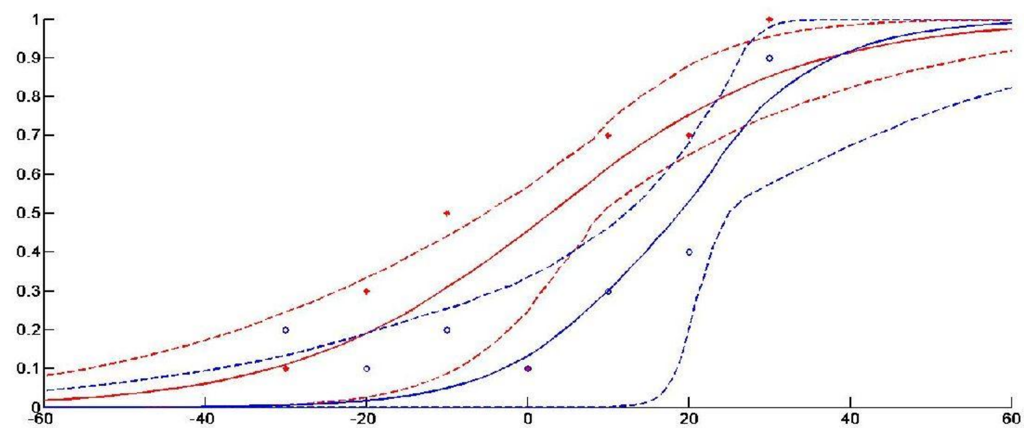

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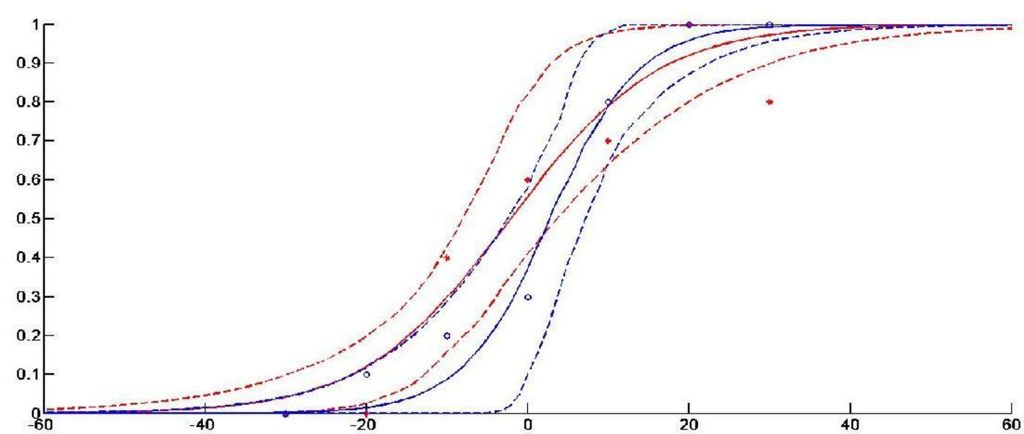

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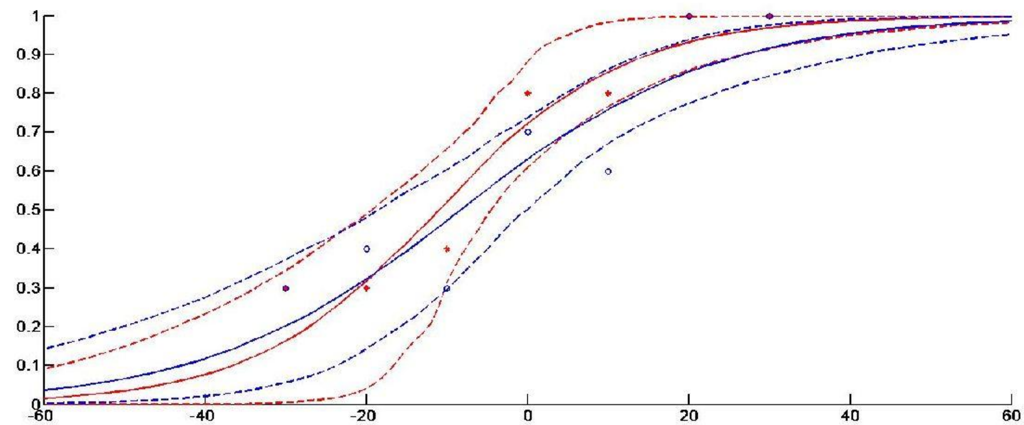

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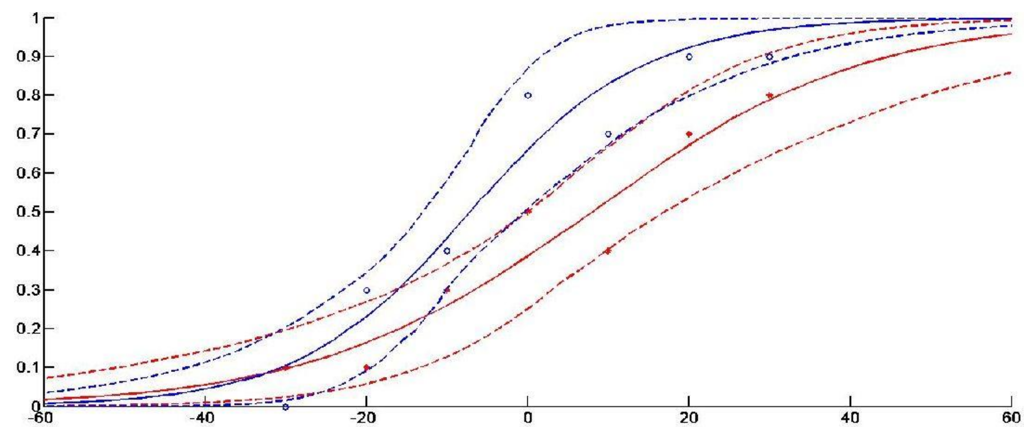

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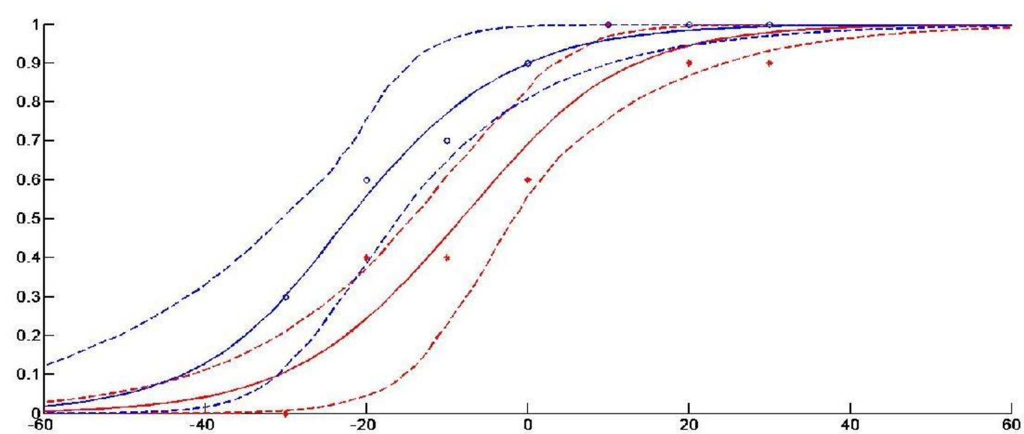

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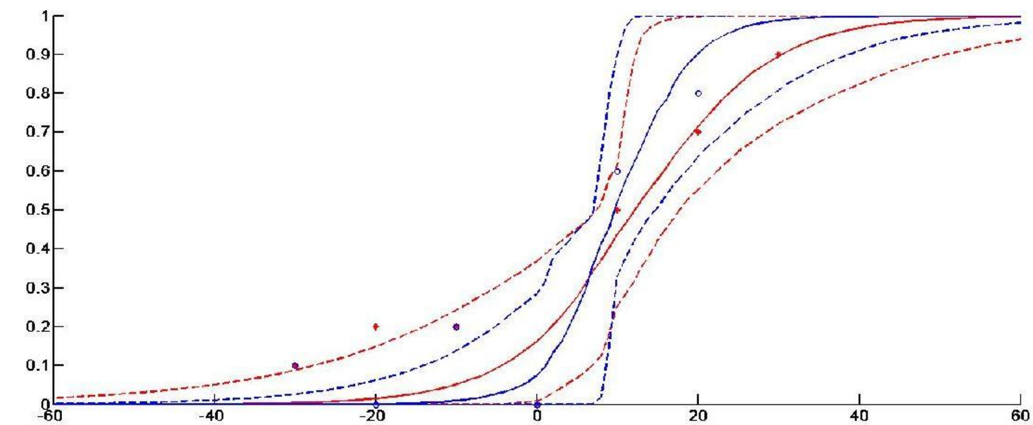

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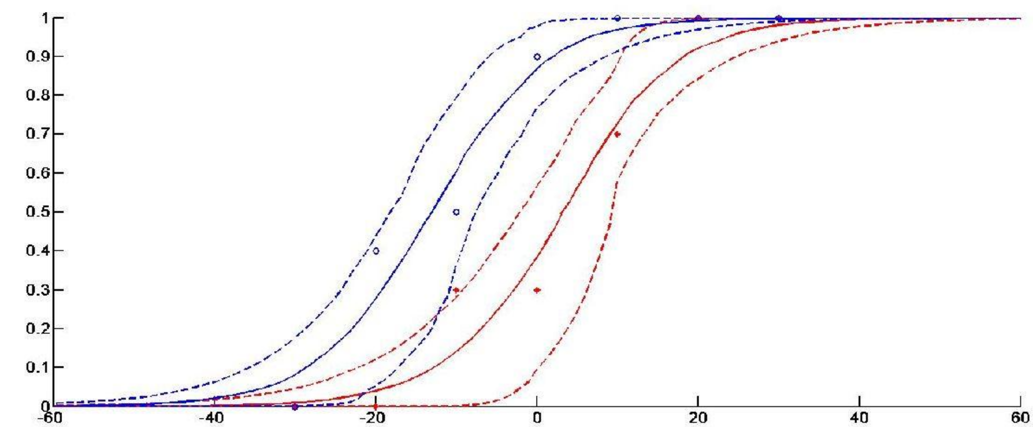

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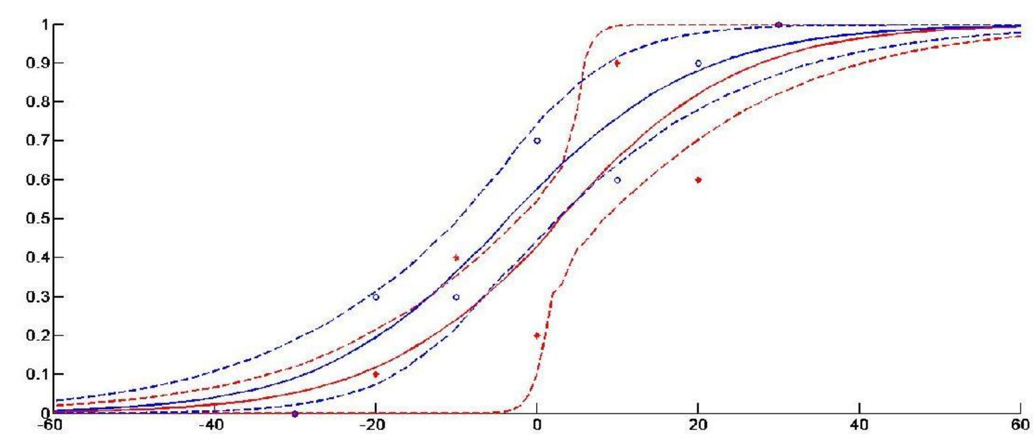

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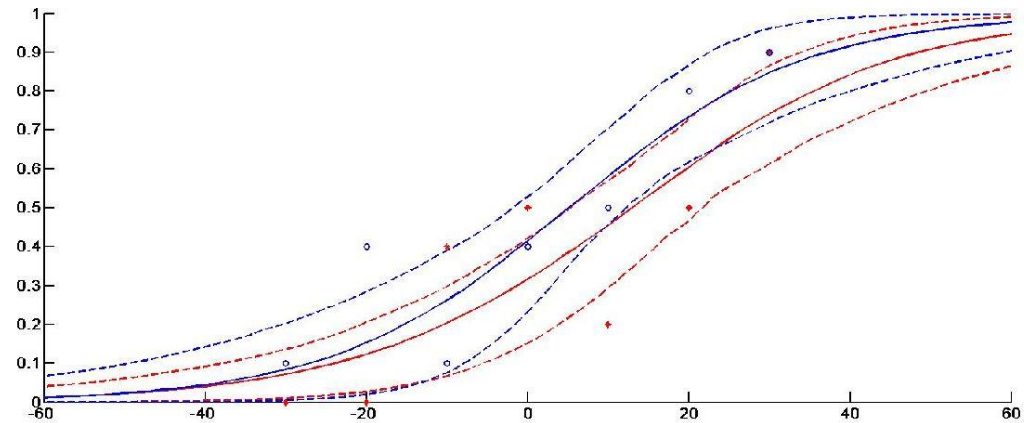

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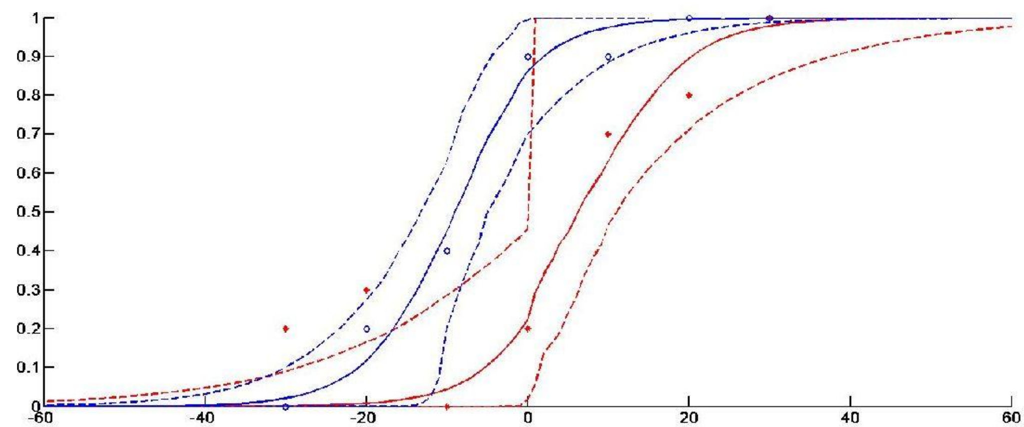

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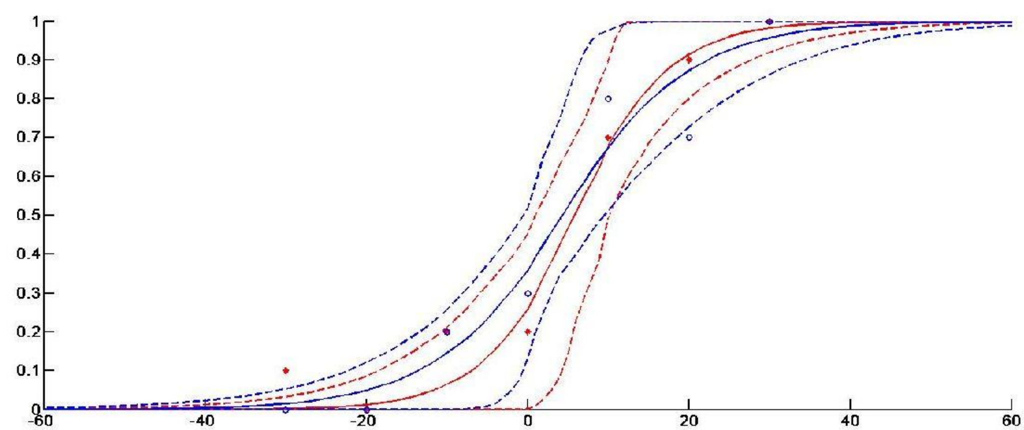

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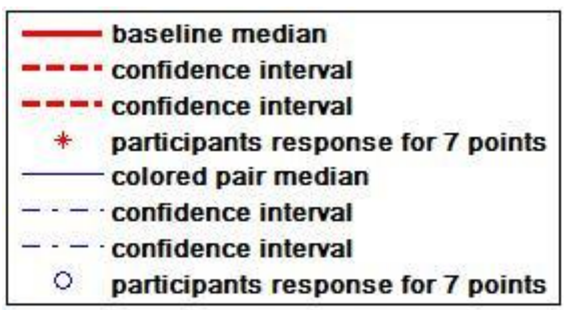
APPENDIX C

Table C.1 The list of color combinations and psychometric curves for Phase2.

	Participant no	Object color	Colored Background Pair	
1	1	orange	cool white light	blue light
2	1	orange	cool white light	green light
3	2	orange	cool white light	green light
4	2	orange	cool white light	red light
5	3	orange	cool white light	blue light
6	3	orange	cool white light	green light
7	3	orange	cool white light	red light
8	4	orange	warm white light	cool white light
9	4	orange	cool white light	blue light
10	4	orange	cool white light	green light
11	4	orange	cool white light	red light
12	5	orange	warm white light	cool white light
13	5	orange	red light	green light
14	6	orange	warm white light	cool white light
15	6	orange	red light	green light
16	7	blue	cool white light	green light
17	7	blue	cool white light	orange light
18	8	blue	warm white light	cool white light
19	8	blue	cool white light	green light
20	9	blue	warm white light	cool white light
21	9	blue	cool white light	orange light
22	9	blue	cool white light	red light
23	10	blue	cool white light	orange light
24	10	blue	cool white light	red light
25	10	blue	red light	green light
26	11	blue	warm white light	cool white light
27	11	blue	cool white light	green light
28	11	blue	red light	green light
29	12	gray	warm white light	cool white light
30	12	gray	cool white light	blue light
31	13	gray	cool white light	blue light
32	13	gray	cool white light	orange light
33	13	gray	red light	green light
34	14	gray	cool white light	green light
35	14	gray	cool white light	red light
36	14	gray	red light	green light

37	15	gray	warm white light	cool white light
38	15	gray	cool white light	green light
39	15	gray	cool white light	red light
40	16	gray	cool white light	orange light
41	16	gray	cool white light	green light
42	16	gray	cool white light	red light
43	16	gray	orange light	blue light
44	17	gray	cool white light	blue light
45	17	gray	cool white light	orange light
46	17	gray	red light	green light
47	17	gray	orange light	blue light
48	14	gray	orange light	blue light
49	18	blue	cool white light	red light
50	19	blue	red light	green light
51	13	gray	warm white light	cool white light

Figure C.1 Psychometric curves for the combinations (Follow according to Table C.1).



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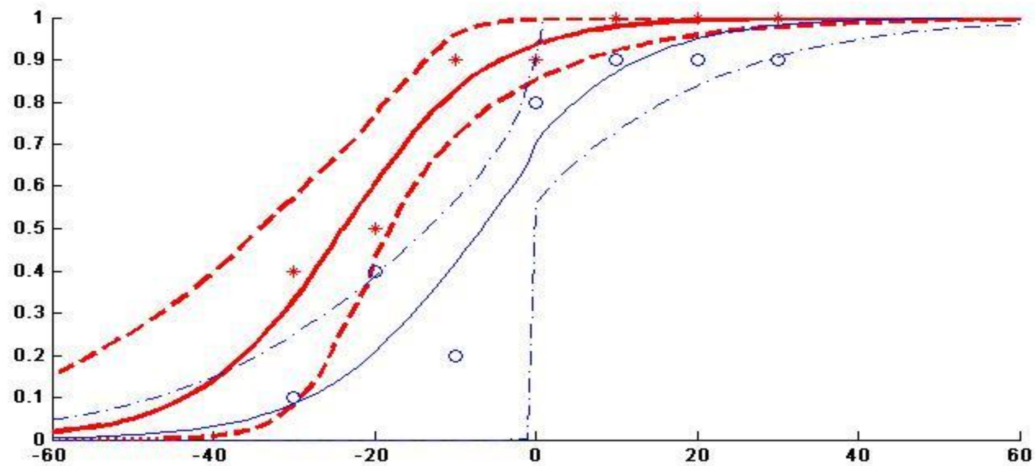
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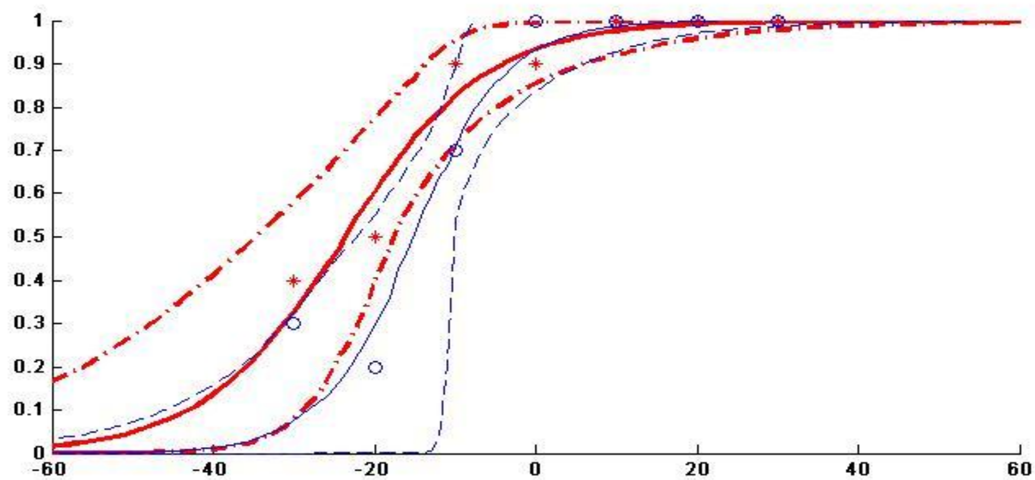
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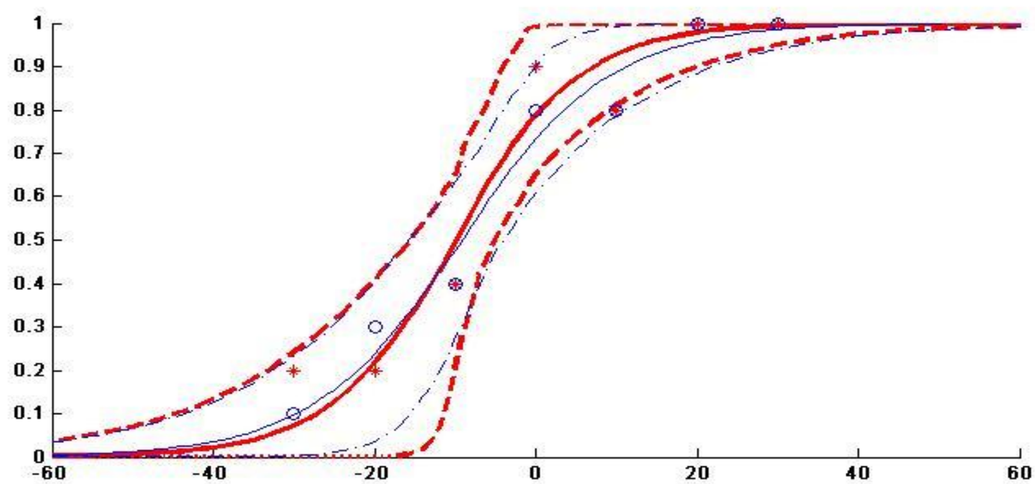
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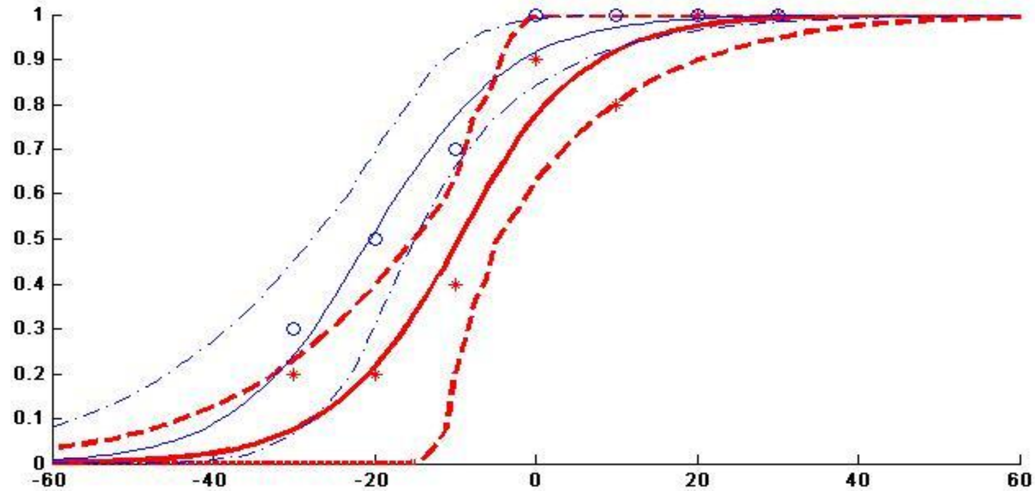
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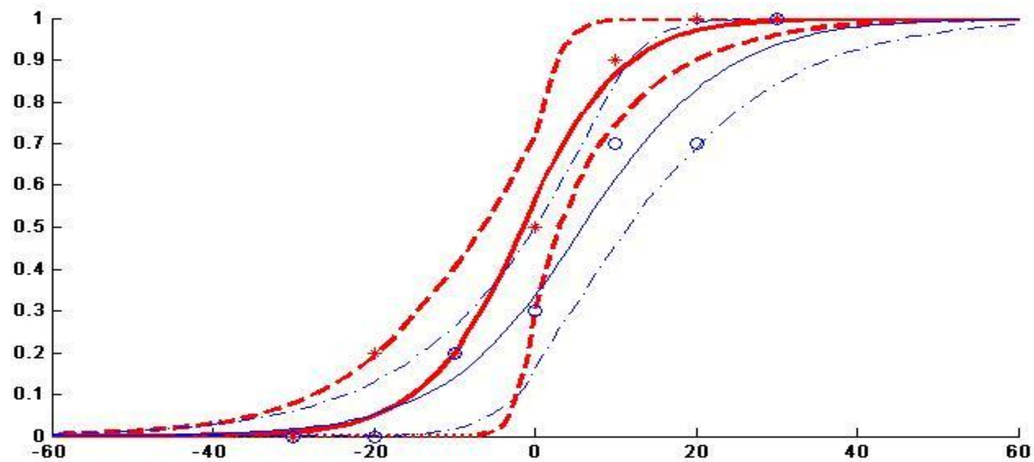
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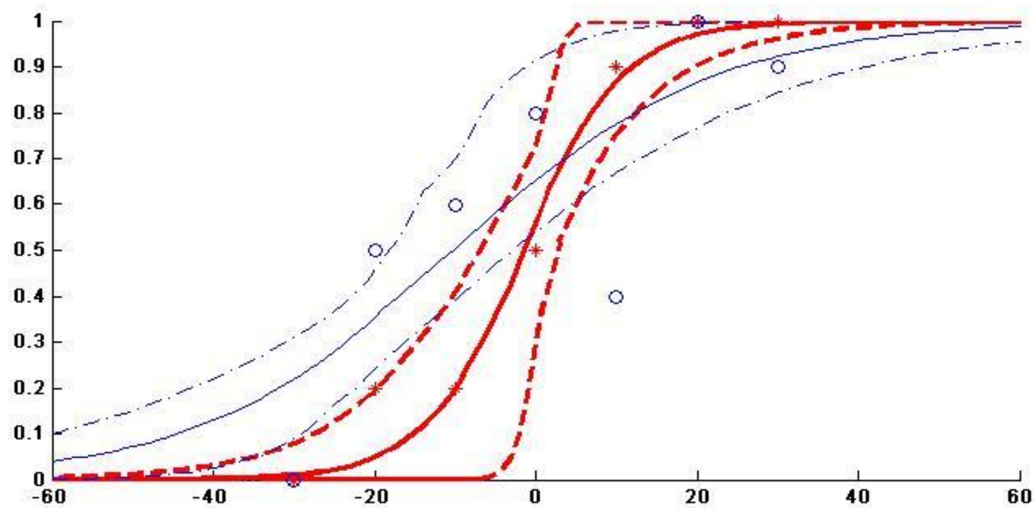
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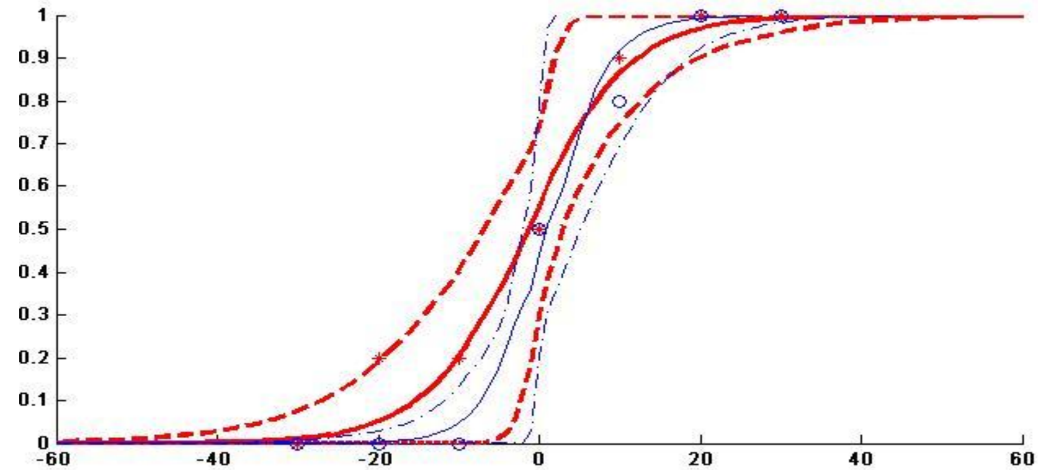

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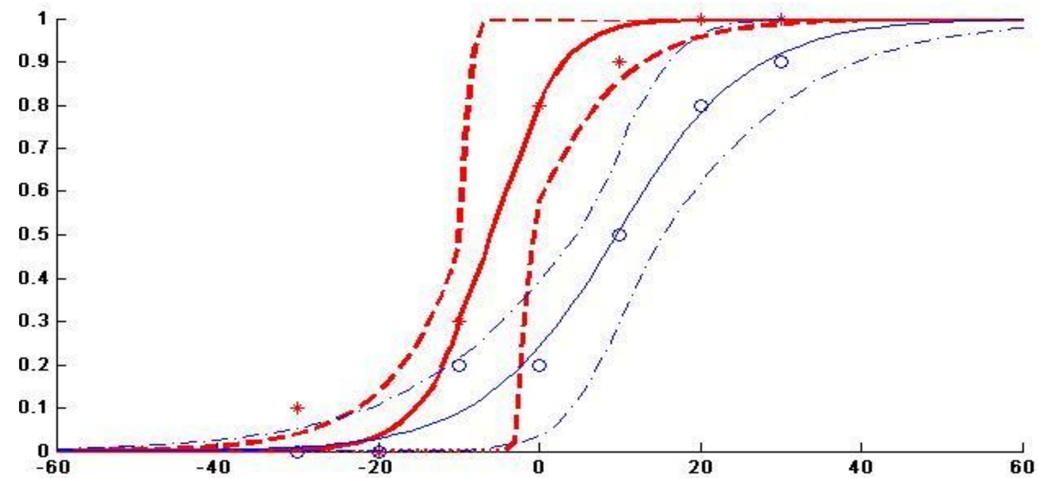

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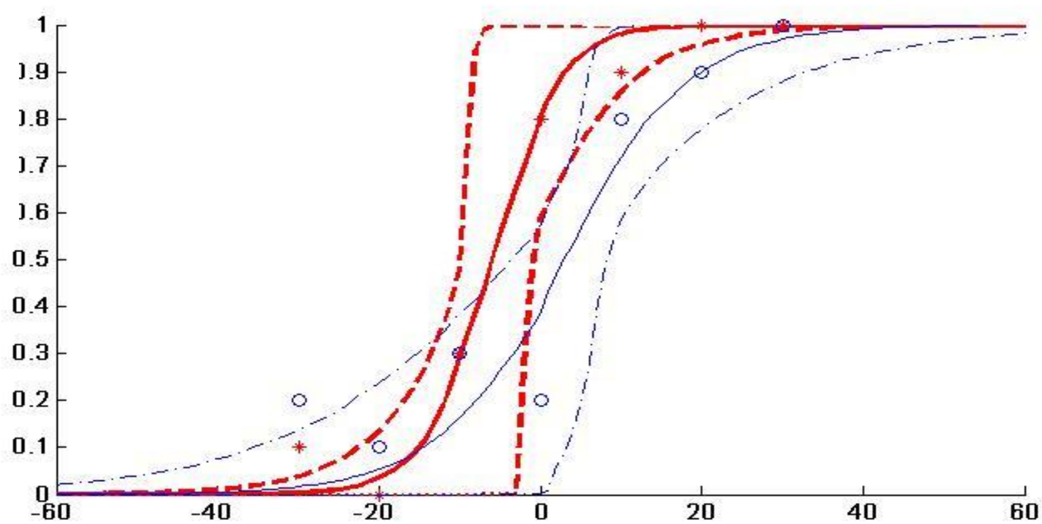

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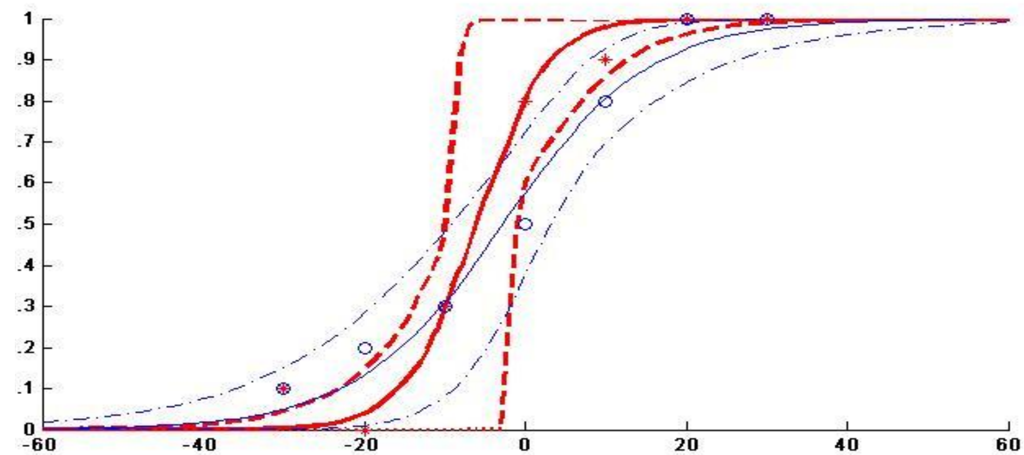

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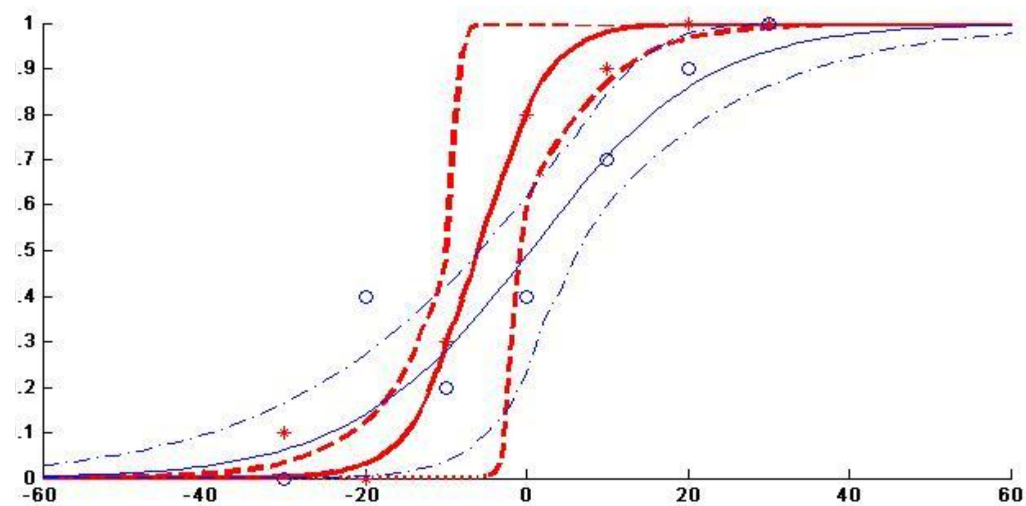

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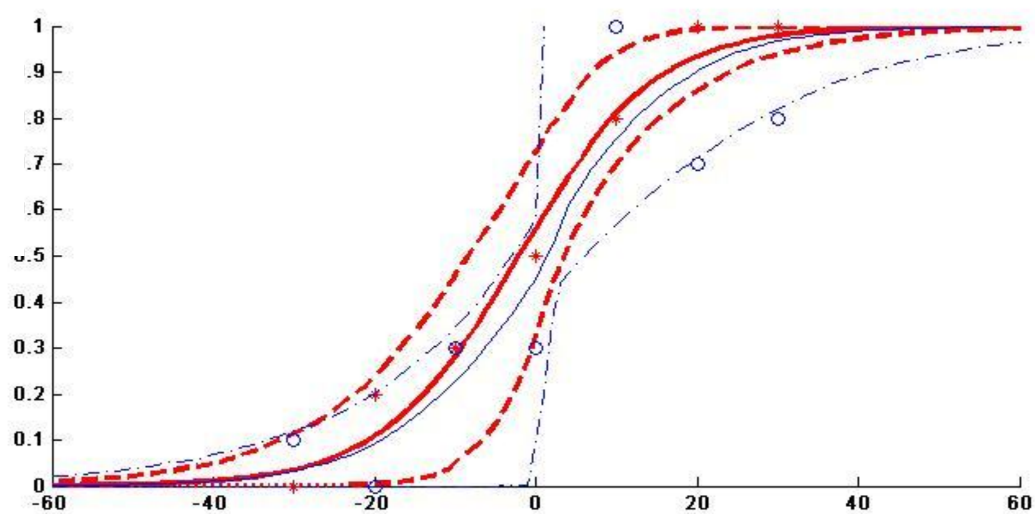

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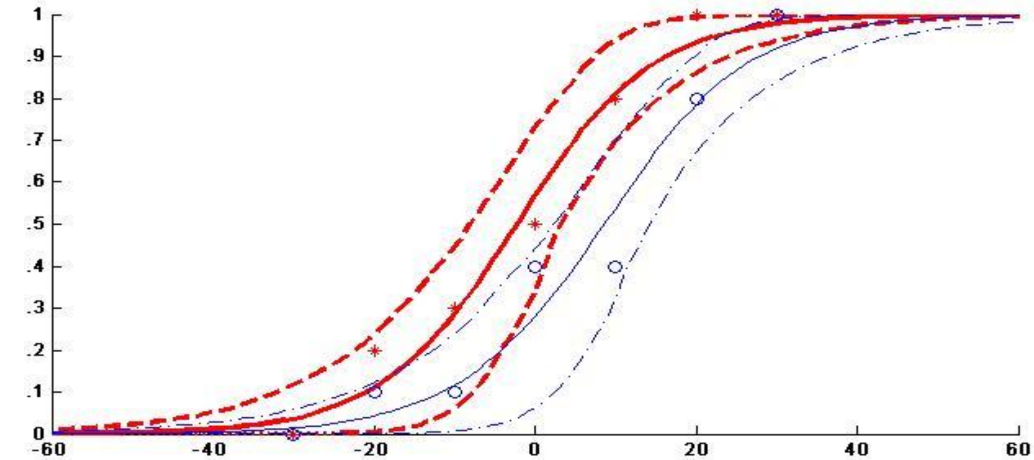
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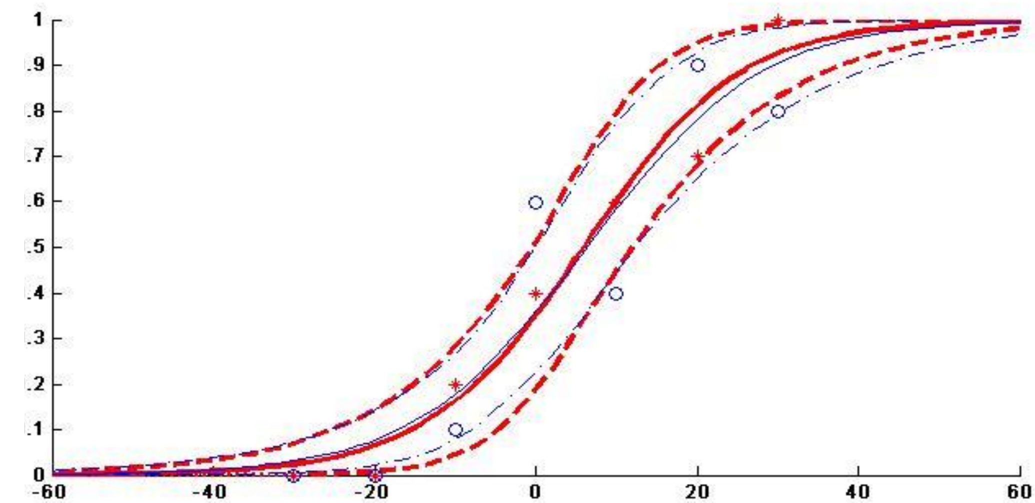
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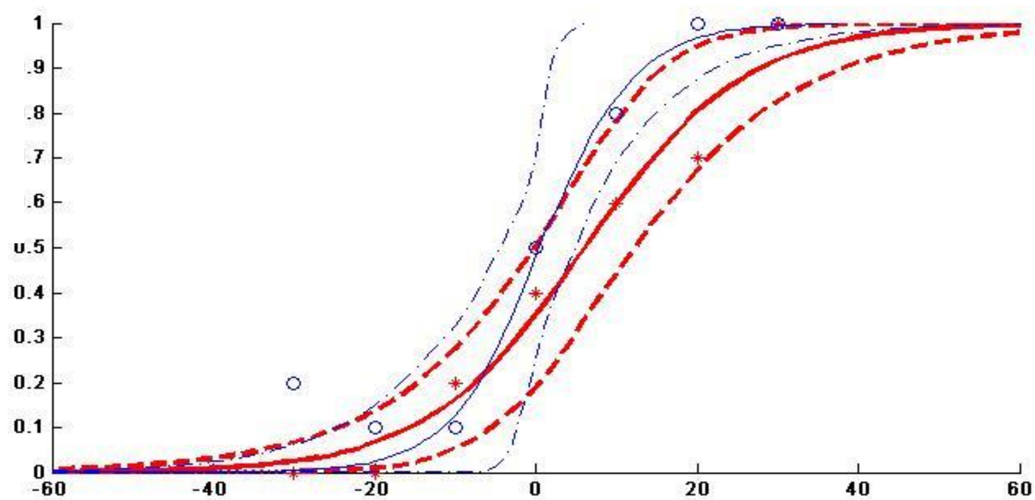
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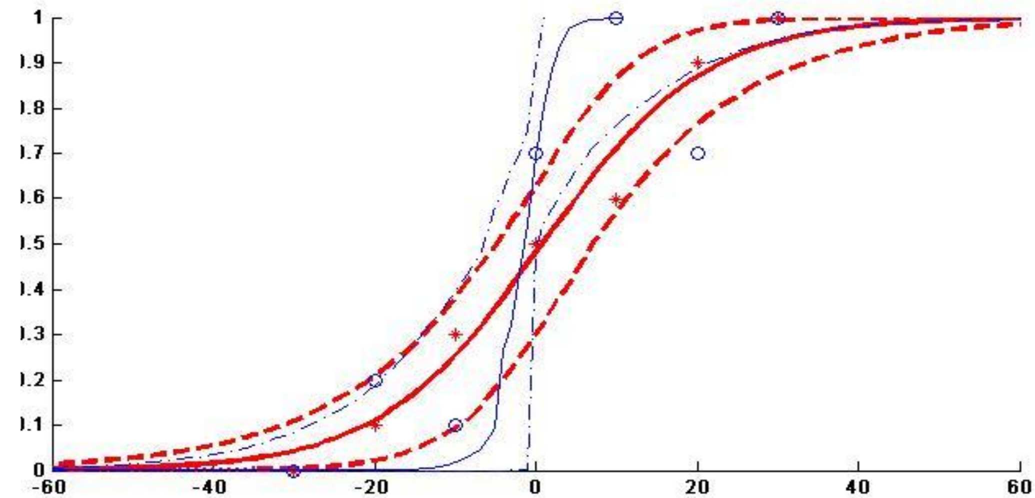
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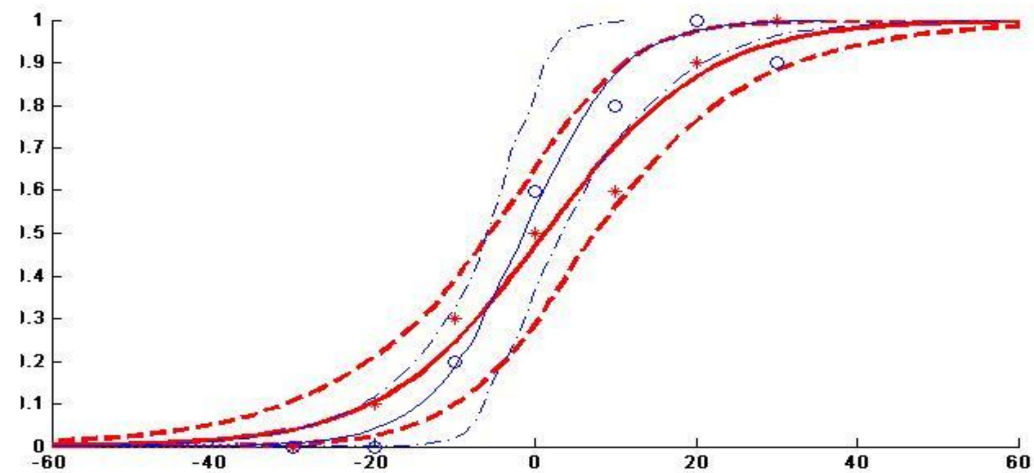
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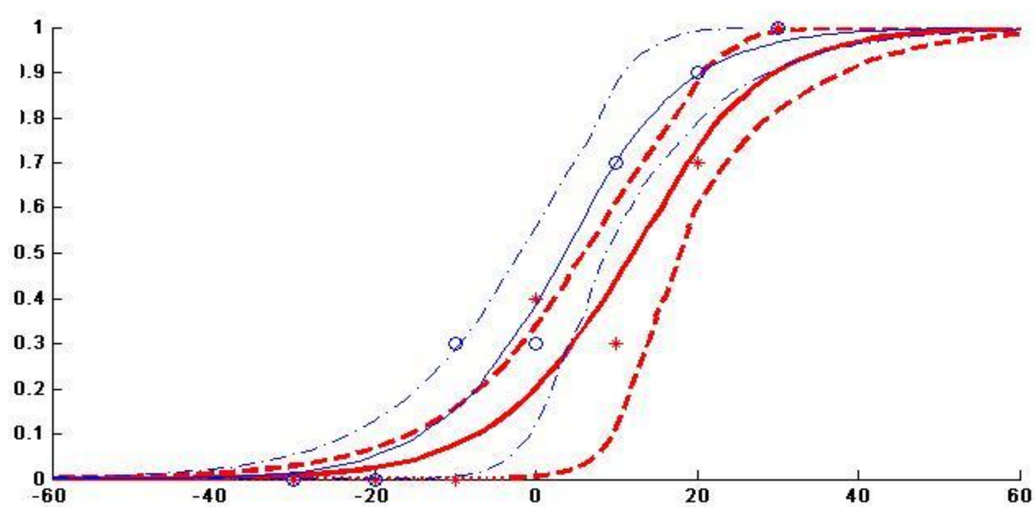
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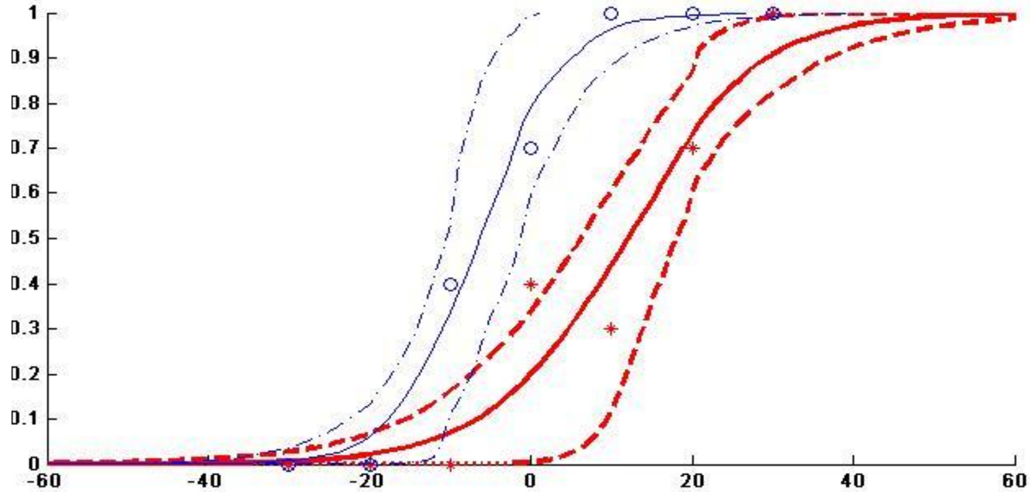

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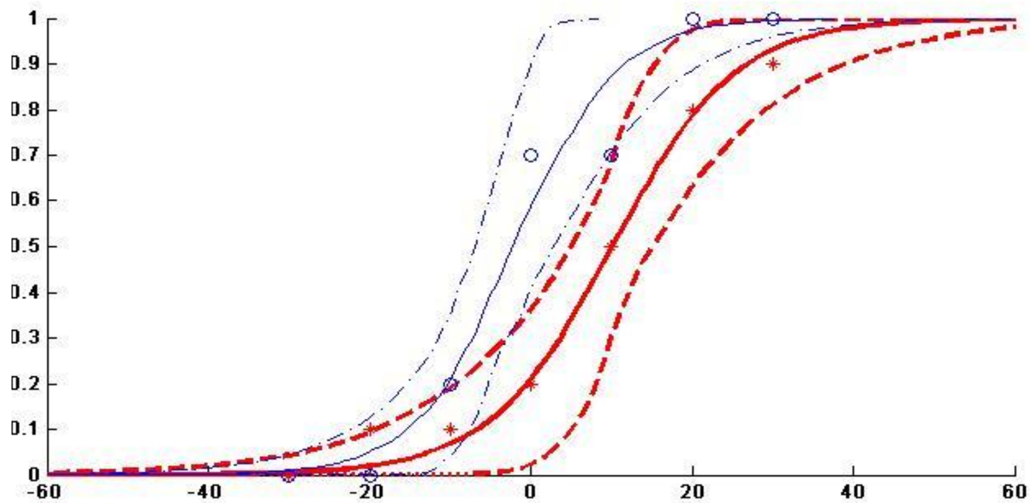

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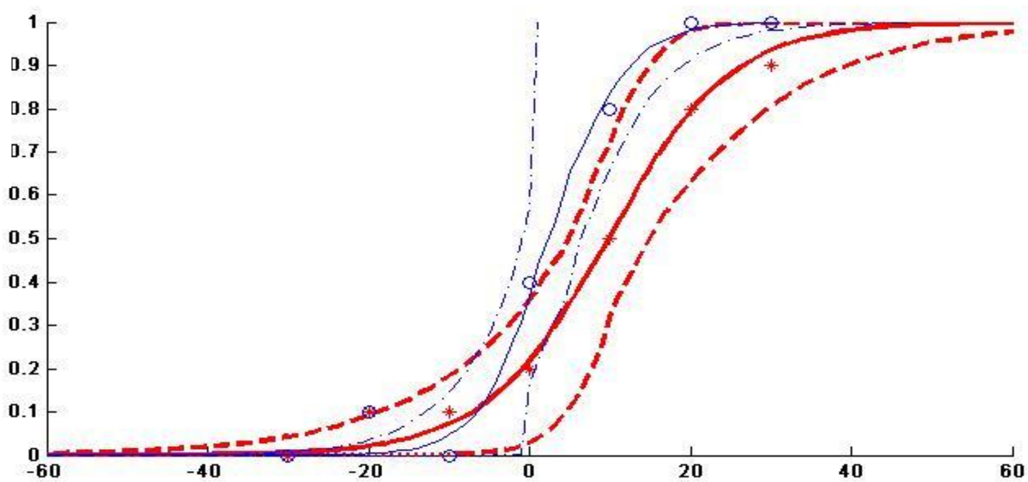

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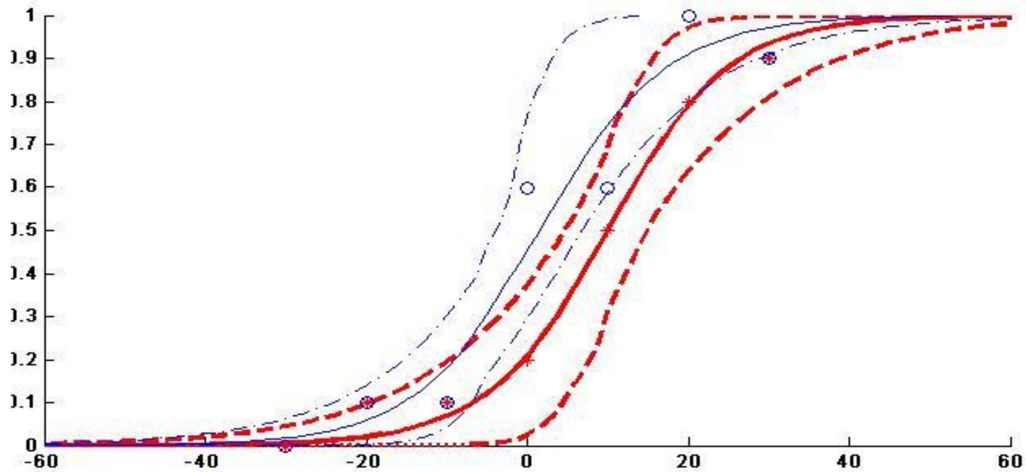
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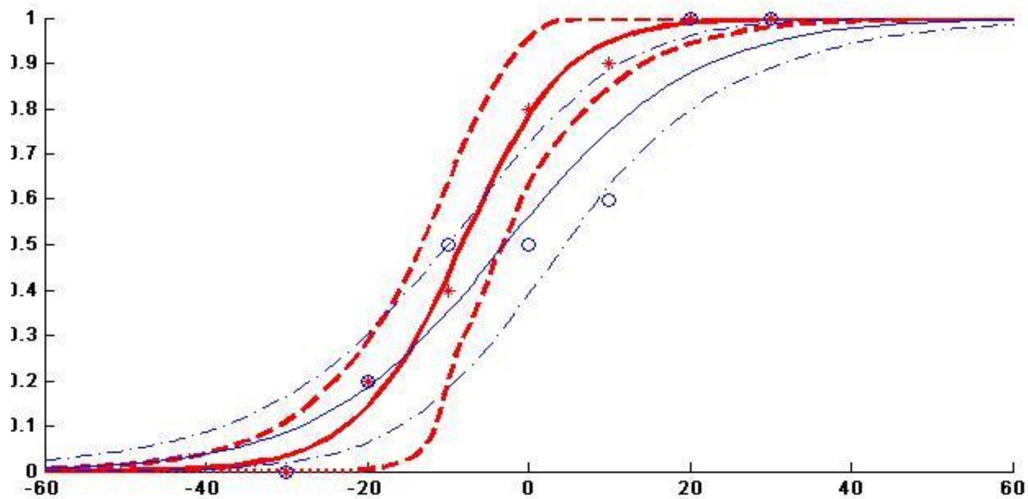
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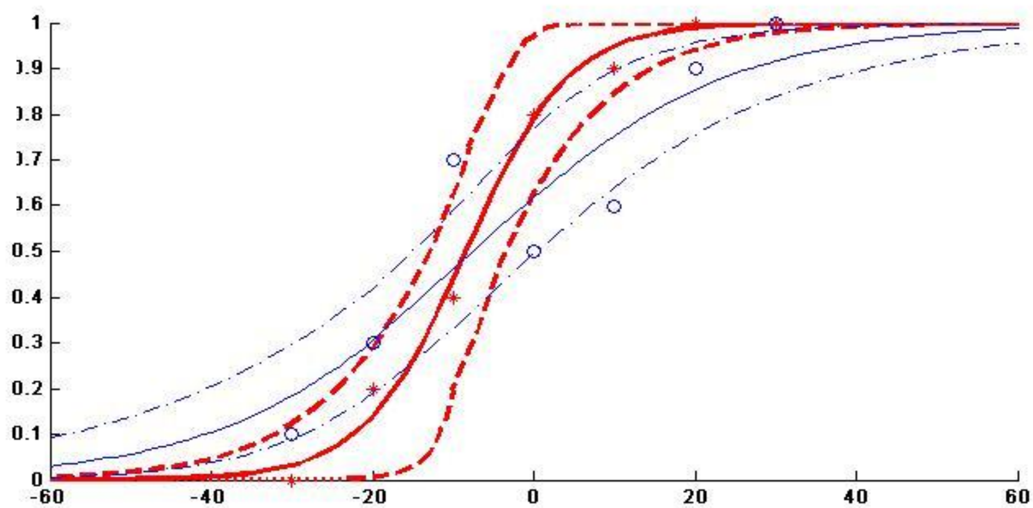
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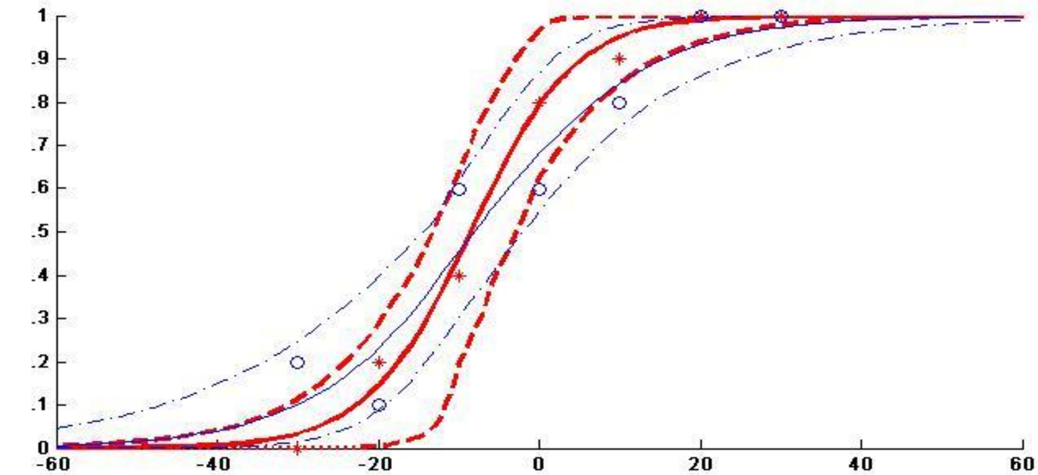
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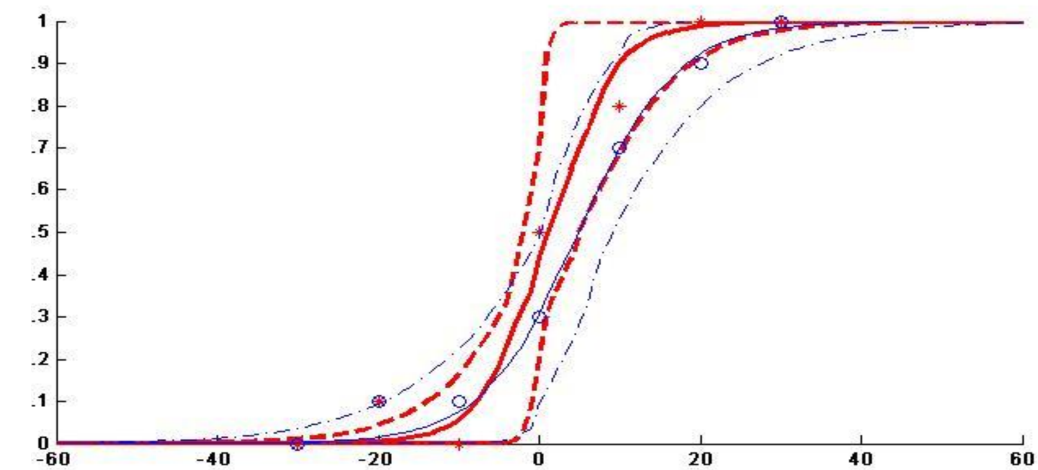
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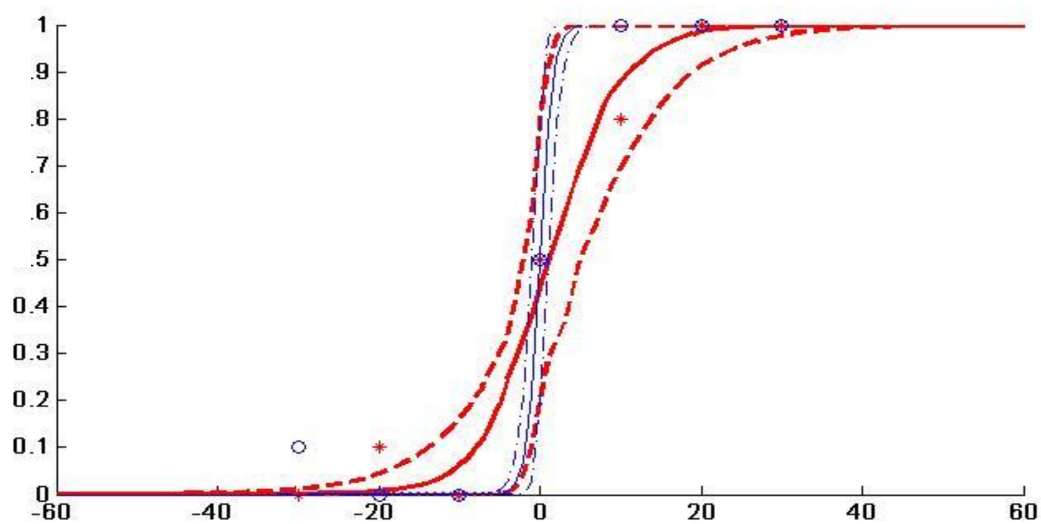
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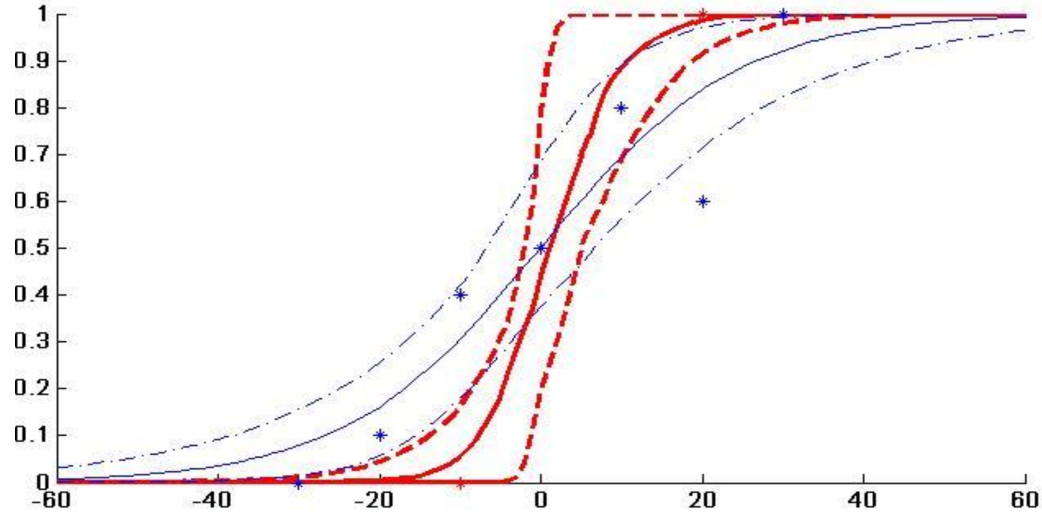
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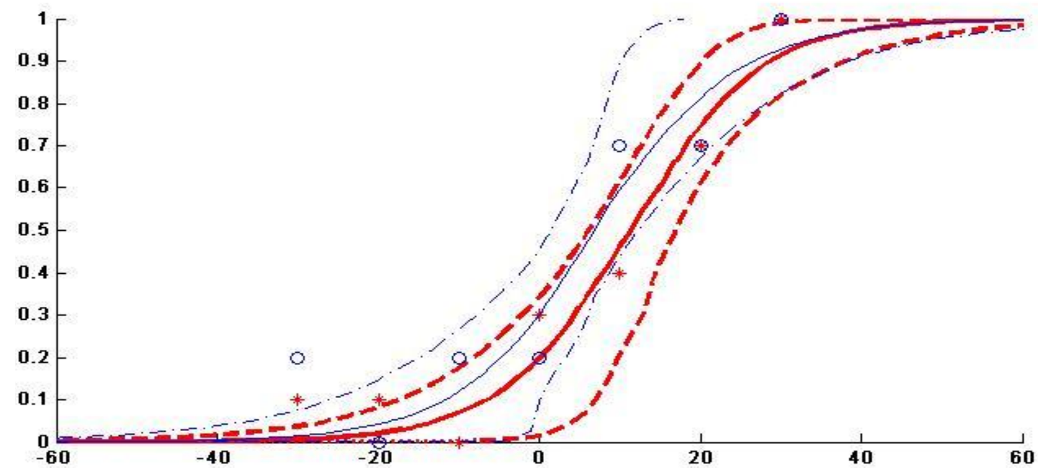
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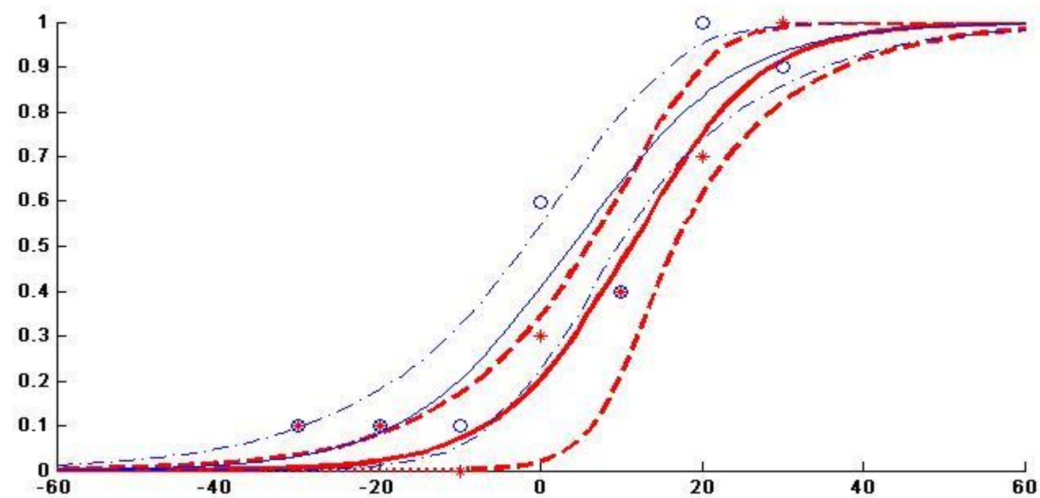
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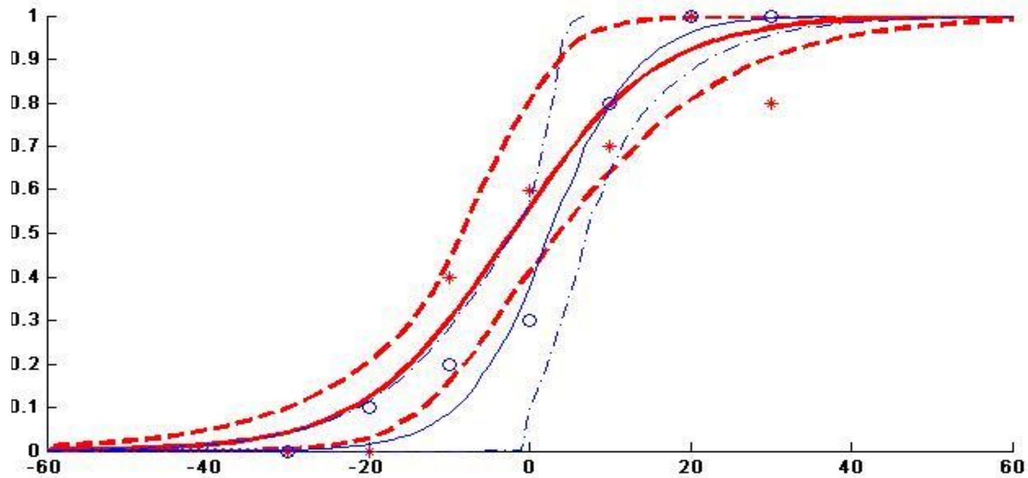
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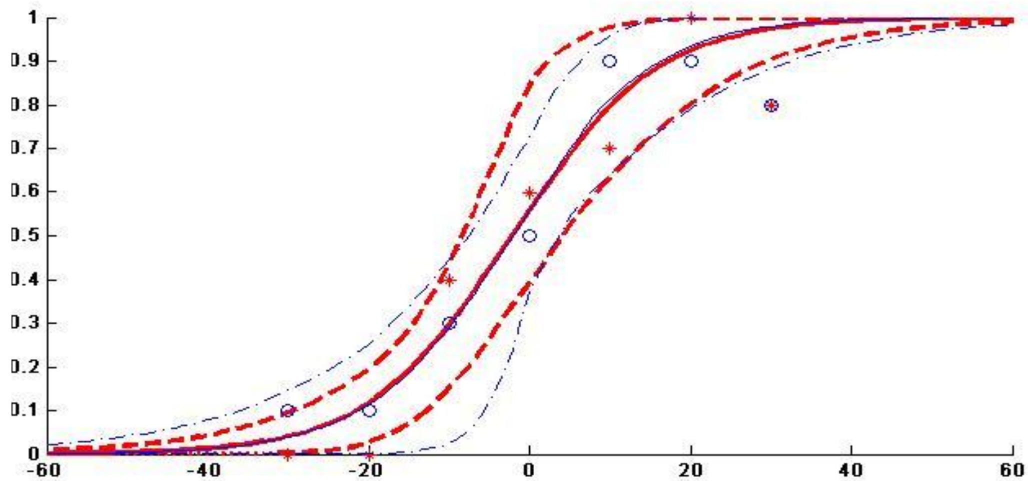
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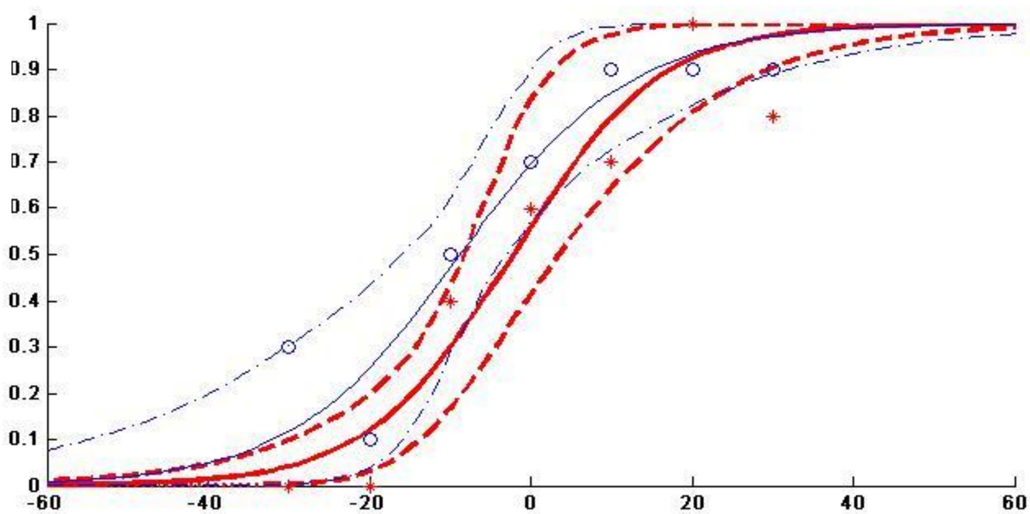
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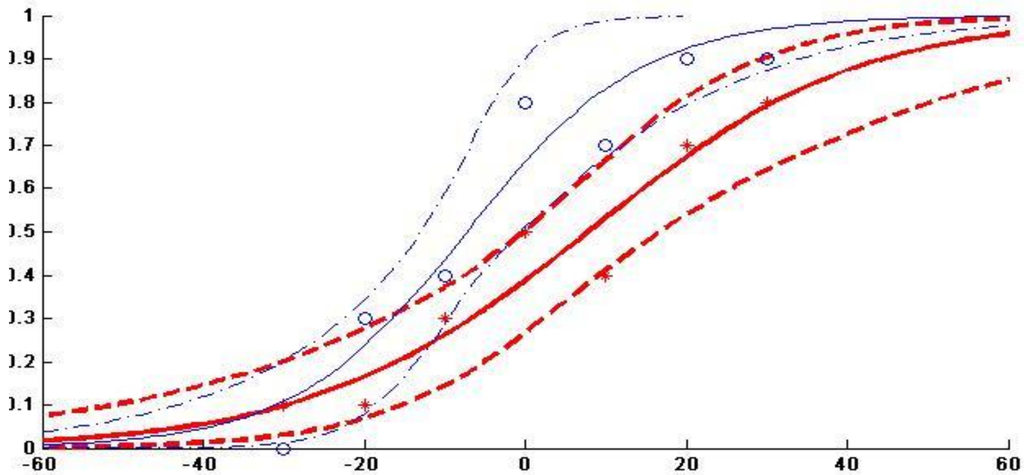
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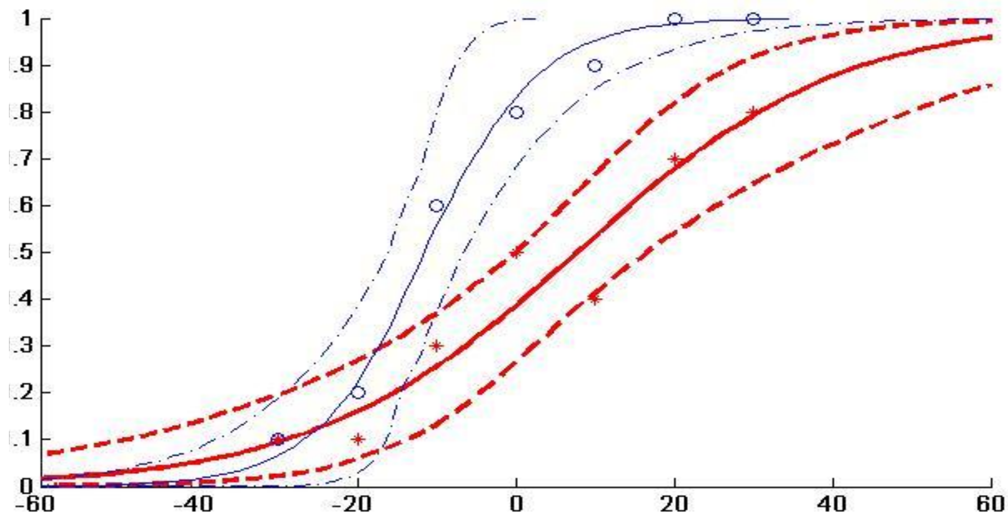
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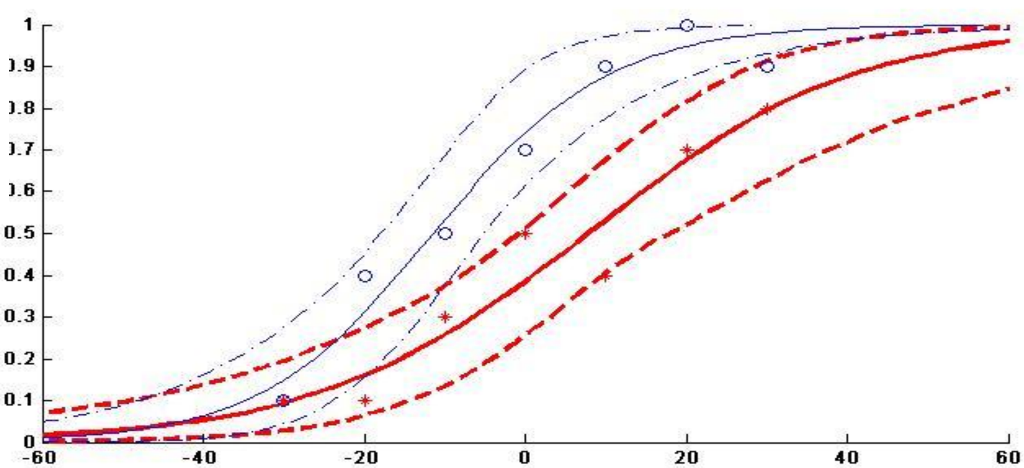
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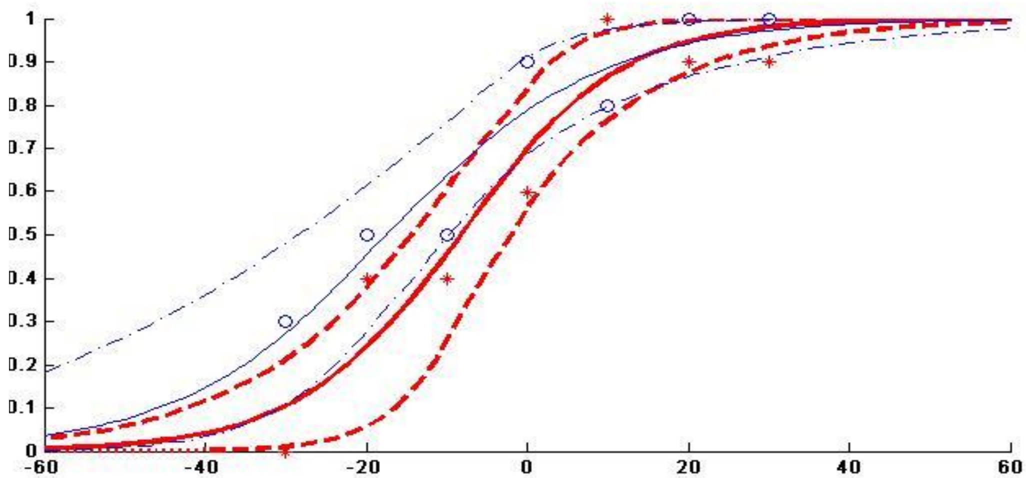
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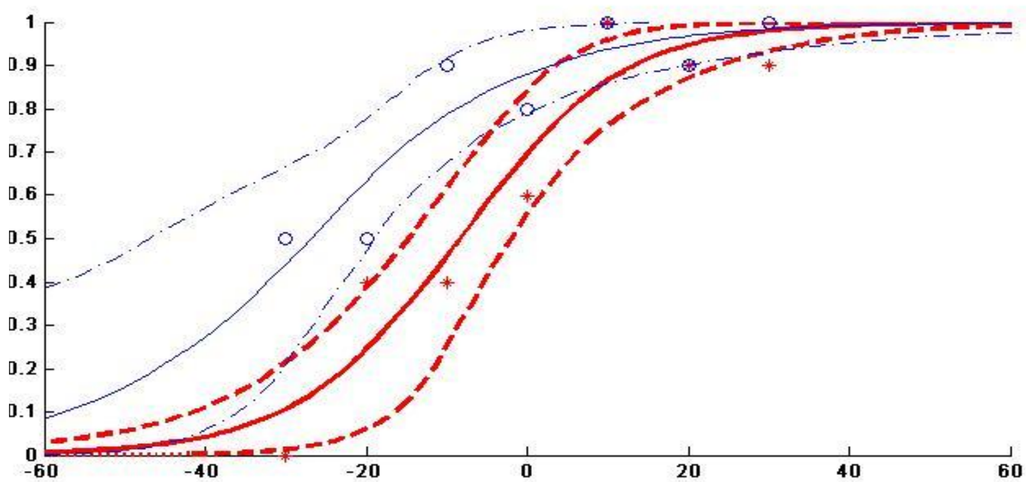
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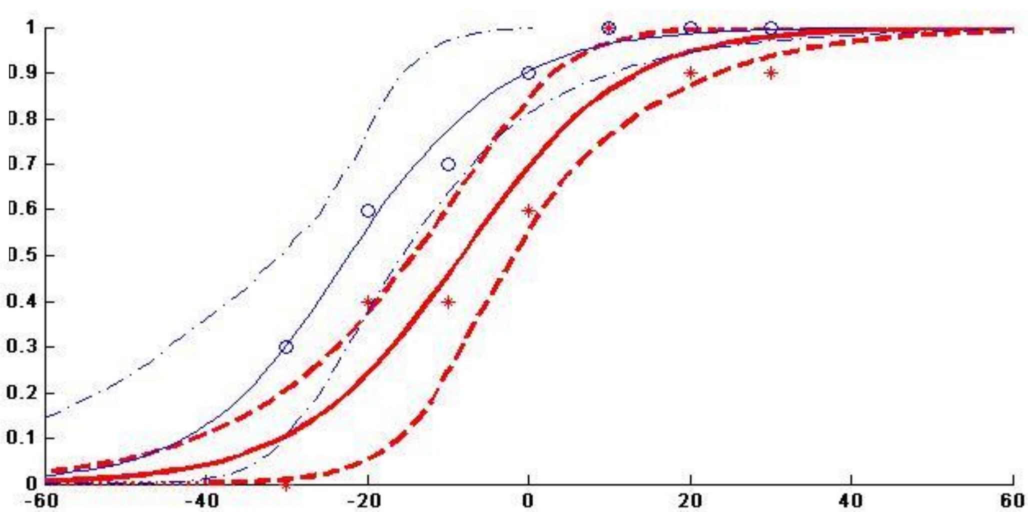
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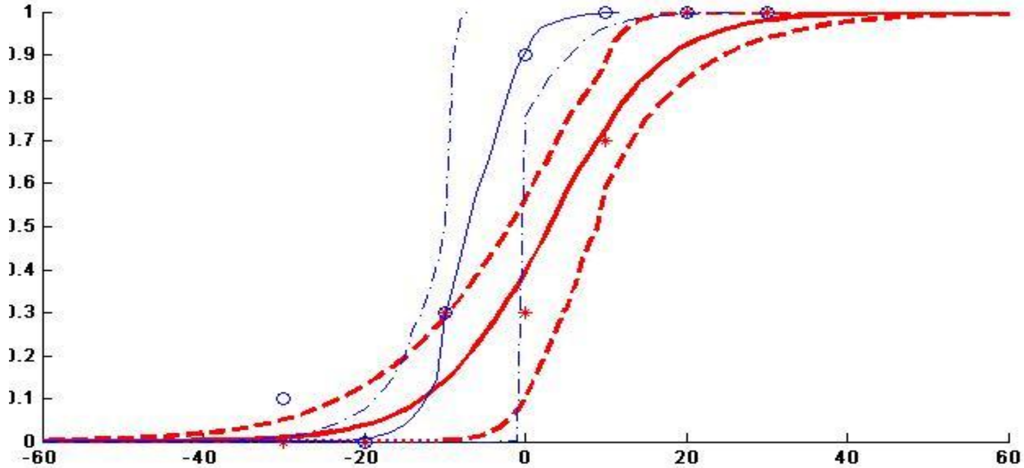
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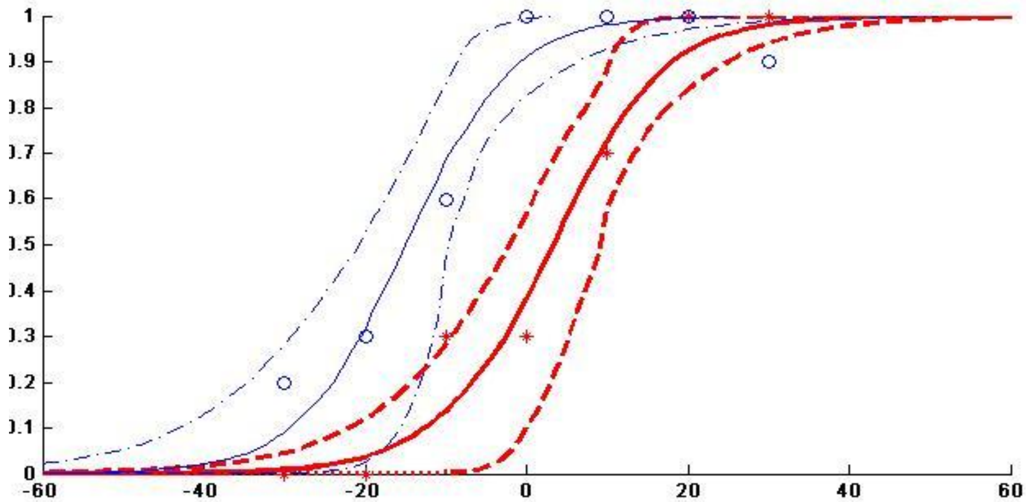
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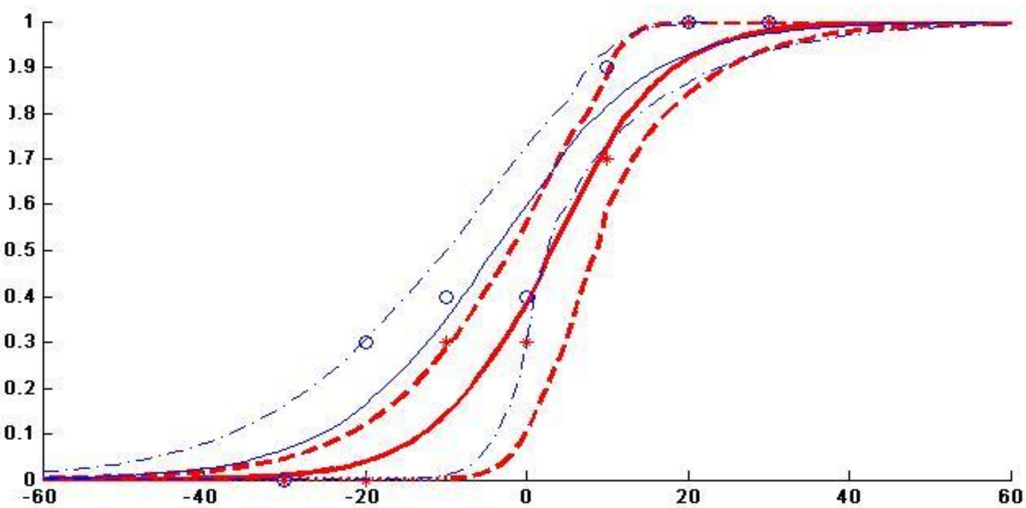
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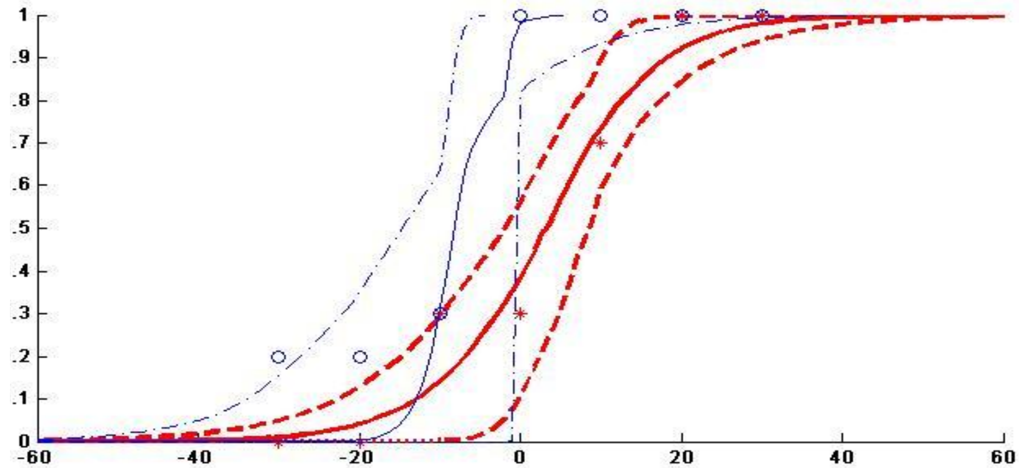
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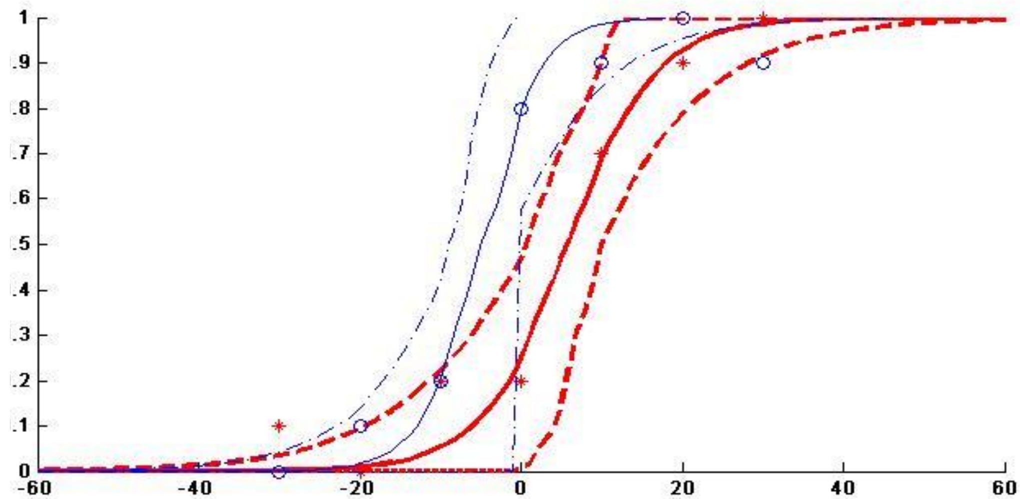
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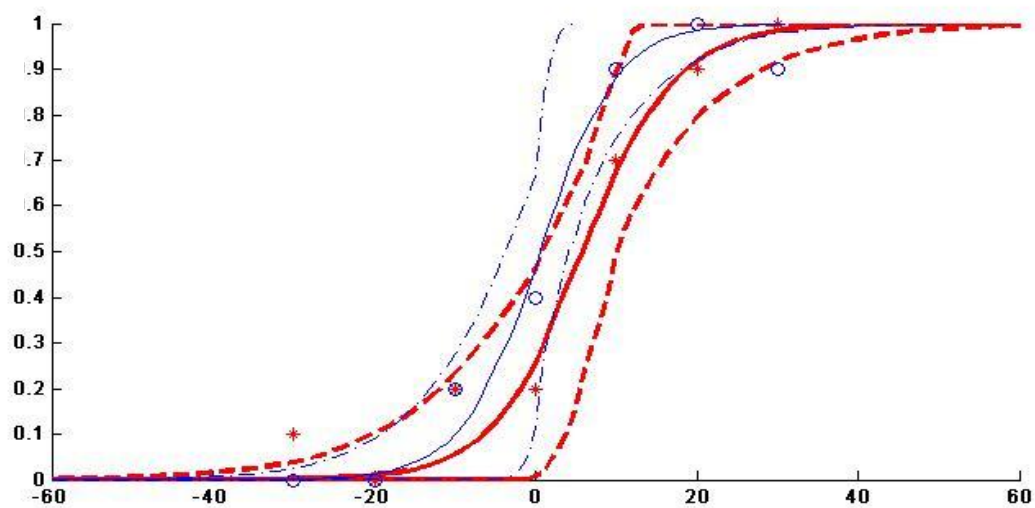
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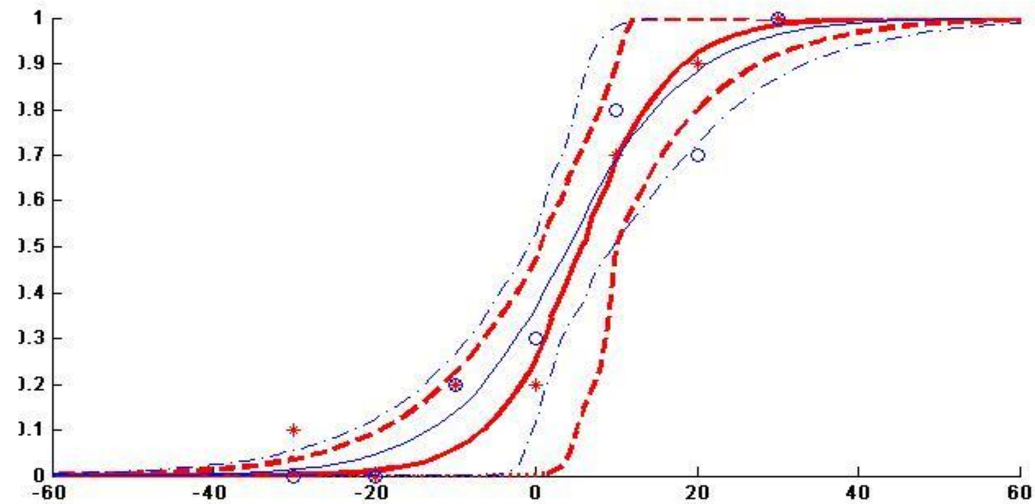
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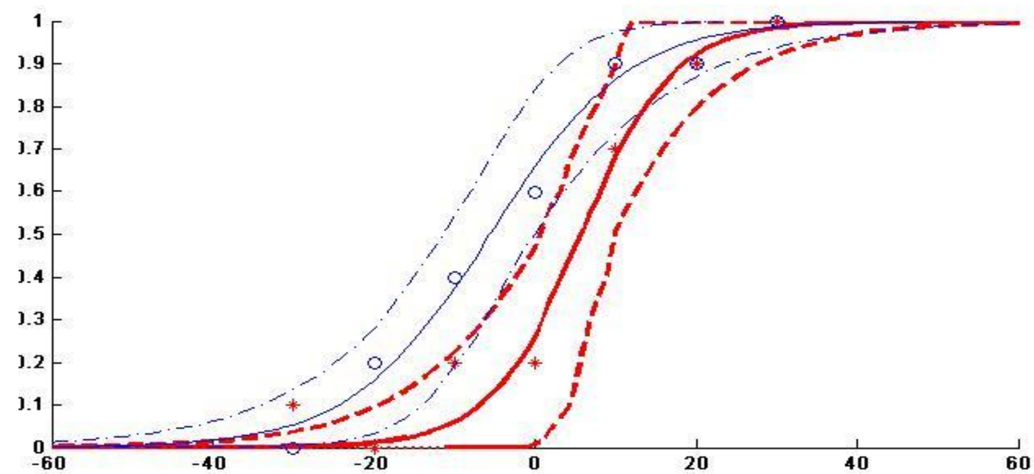
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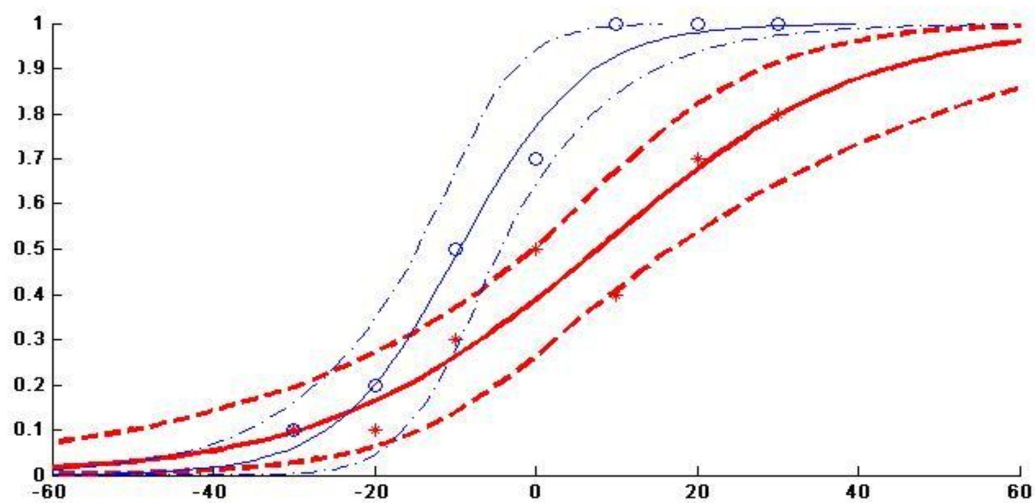
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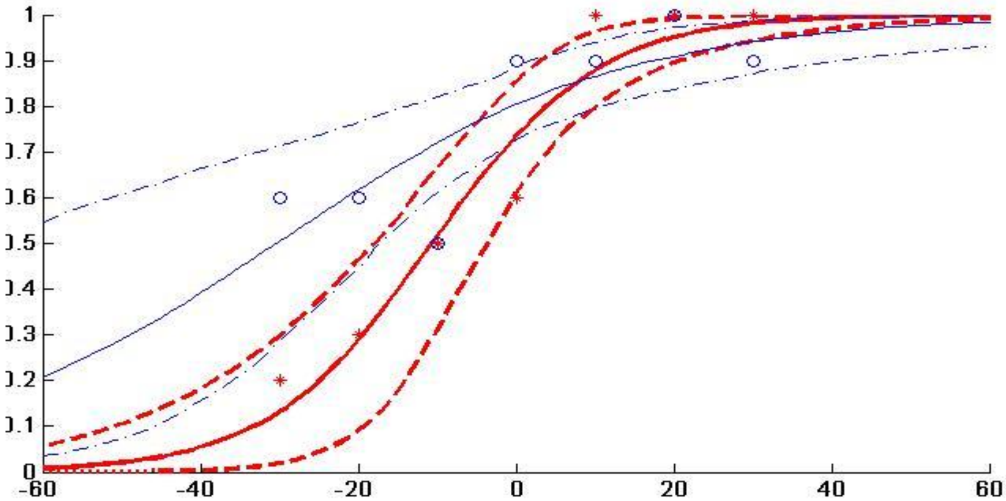
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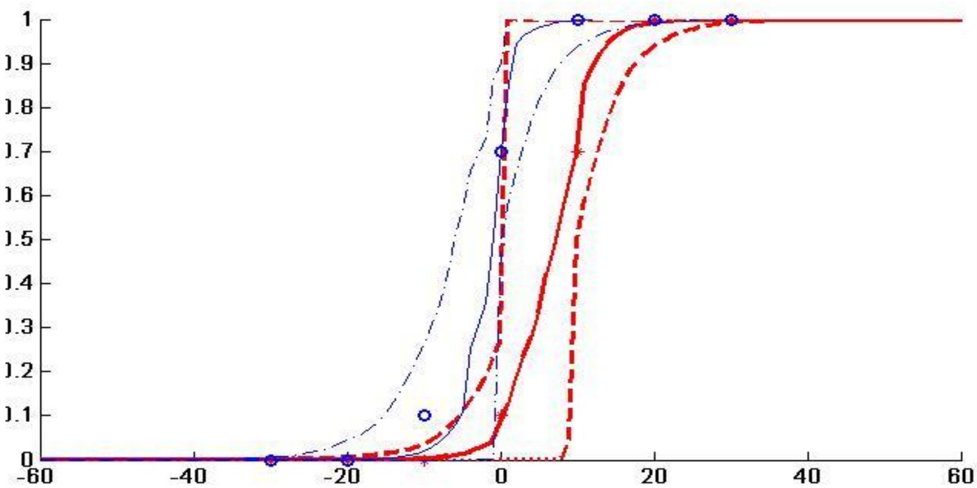
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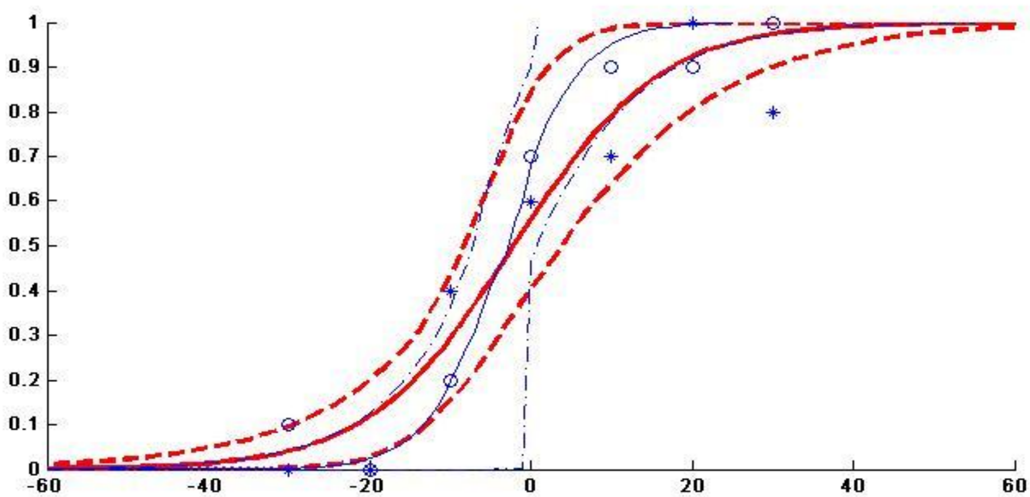
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APPENDIX D

Statistical results of the Experiment

Table D.1.Univariate analysis of variance

Tests of Between-Subjects Effects

Dependent Variable:Value

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[b]
Corrected Model	2549,522[a]	16	159,345	2,971	,004	,583	47,543	,980
Intercept	642,173	1	642,173	11,975	,001	,260	11,975	,919
O_Color * Pair	115,972	8	14,497	,270	,971	,060	2,163	,120
Pair	782,892	6	130,482	2,433	,046	,300	14,599	,746
O_Color	1483,602	2	741,801	13,833	,000	,449	27,666	,997
Error	1823,254	34	53,625					
Total	5381,505	51						
Corrected Total	4372,776	50						

a. R Squared = ,583 (Adjusted R Squared = ,387)

b. Computed using alpha = ,05

Table D.2. Post Hoc Tests – Object homogenous subsets

Value

	O_color	N	Subset 1	Subset 2
Hochberg[a,b,c]	,00	15	-3,9669	
	1,00	15		5,5693
	2,00	21		9,6800
	Sig.		1,000	,301

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 16,579.

b. Alpha = ,05.

Table D.3. Post Hoc Tests – Pair homogenous subsets

Value

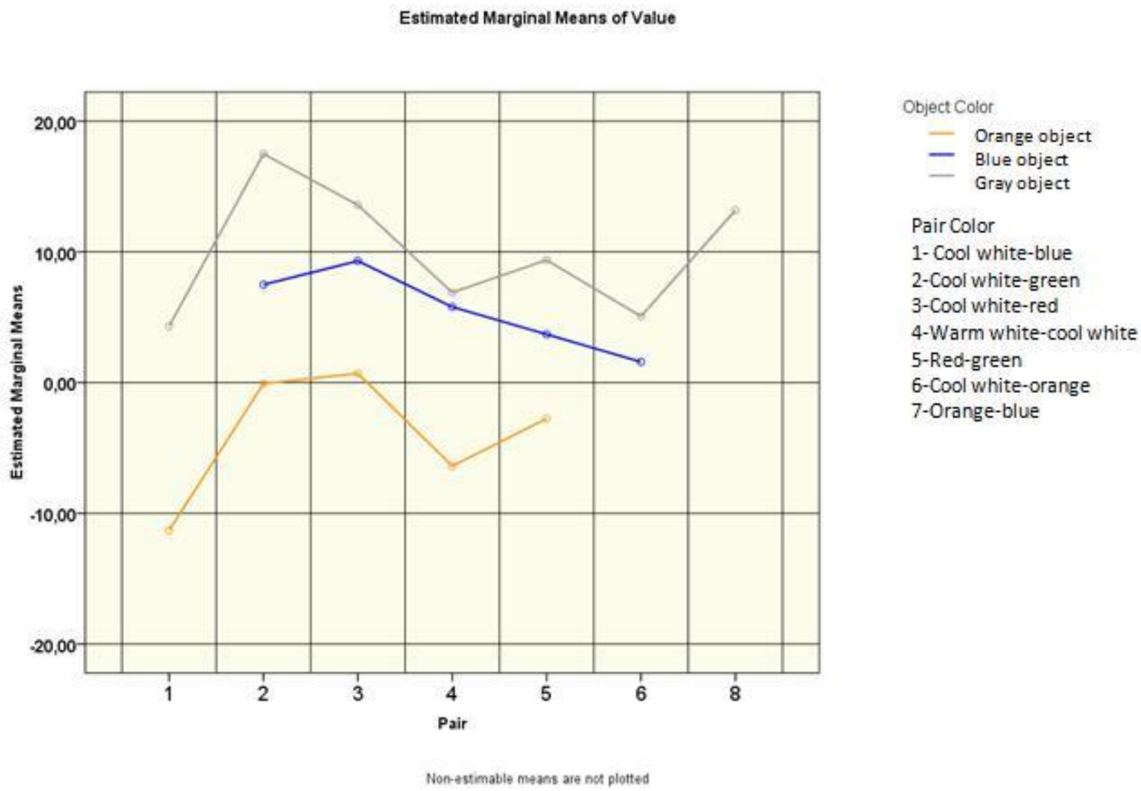
	Pair	N	Subset 1	Subset 2
Hochberg[a,b,c]	1,00	6	-3,4963	
	4,00	9	1,3876	1,3876
	6,00	6	3,3232	3,3232
	5,00	9	3,4332	3,4332
	3,00	9	7,8606	7,8606
	2,00	9	8,2970	8,2970
	7,00	3		13,1827
	Sig.		,130	,130

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 16,579.

b. Alpha = ,05

Figure D.1. Interaction table of object color and background hue pairs



APPENDIX E

General Presentation of Data

Table E.1. Data for first and second phase of the experiment with differences and significances of the color combinations.

RESULTS FOR FIRST AND SECOND PHASE OF THE EXPERIMENT																	
object color	Background.	Sig.-not sig.				Plot numbers on the lists				Differences				Significances			
orange	cw-bl	+	+	+	-	1	5	9	pre5	-17.6832	-7.3642	-8.8583	-5.7	0.003	0.044	0.04	0.186
orange	cw-gr	-	-	-	-	2	6	3	pre6	-8.6059	8.8882	-0.5582	7	0.063	0.056	0.448	0.497
orange	cw-rd	+	-	-	-	4	7	11	pre7	11.0747	-2.5674	-6.4115	-26.7	0.015	0.251	0.088	0.066
orange	ww-cw	+	-	-	+	8	14	12	pre4	-15.4866	-0.2299	-3.4317	-15	0	0.479	0.21	0.0001
orange	rd-gr	+	-	-	+	13	15	10	pre10	-10.7927	5.855	-3.3323	10.3	0.022	0.109	0.248	0.018
orange	ww-bl	-				pre1				-4.7				0.188			
orange	ww-rd	-				pre3				6				0.107			
orange	ww-gr	-				pre2				5				0.187			
orange	bl-rd	+				pre9				-16.4				0.021			
orange	bl-gr	-				pre8				-0.1				0.487			
blue	cw-gr	-	-	-	-	16	19	27	pre16	2.8666	18.4956	1.109	1.1	0.246	0	0.318	0.334
blue	cw-or	-	-	-	-	17	21	23	pre15	2.7644	7.3754	-5.4015	-5.2	0.289	0.034	0.157	0.155
blue	ww-cw	+	+	-	+	18	20	26	pre14	8.6172	12.271	-3.5334	12	0.042	0.003	0.183	0.004
blue	cw-rd	+	-	+		22	24	49	-----	8.536	-0.629	20	-----	0.026	0.461	0.031	-----
blue	rd-gr	-	-	+		25	28	50	-----	-0.0606	1.1284	10	-----	0.493	0.408	0.005	-----
blue	ww-or	-				pre11				6				0.12			
blue	ww-gr	-				pre12				3.5				0.394			
blue	ww-rd	-				pre13				9				0.025			
blue	or-rd	+				pre19				5.7				0.034			
blue	or-gr	+				pre18				11				0.023			
gray	ww-cw	-	-	-	+	29	37	51	pre25	4.5664	9.215	0.5	-15.8	0.147	0.053	0.427	0.015
gray	cw-bl	-	-	+	-	30	31	44	pre26	7.5374	-4.6419	10.0324	-5	0.058	0.139	0.005	0.147
gray	cw-or	-	+	-	-	32	40	45	pre27	0.0022	9.8837	5.3151	-2.6	0.499	0.02	0.076	0.363
gray	rd-gr	-	+	-	-	33	36	46	pre35	6.8668	19.575	1.6595	1.3	0.103	0.001	0.352	0.367
gray	cw-gr	+	+	+	+	34	38	41	pre28	15.1499	18.7626	18.5652	14.9	0.008	0.008	0	0.009
gray	cw-rd	+	+	-	+	35	39	42	pre29	19.2741	14.1685	7.3002	13	0.001	0.005	0.082	0.005
gray	or-bl	+	+	+	-	43	47	48	pre30	10.8493	11.2526	17.4462	2.7	0.026	0.004	0.008	0.289
gray	ww-bl	-				pre21				-0.7				0.426			

gray	ww-or	-				pre22				-8.5				0.089			
gray	ww-gr	+				pre23				11.35				0.007			
gray	ww-rd	-				pre24				6.7				0.157			
gray	or-gr	+				pre31				16				0.002			
gray	or-rd	-				pre32				6.5				0.1007			
gray	bl-gr	-				pre33				8				0.115			
gray	rd-bl	+				pre34				15.9				0.0005			

Notes: In the table, significant and not significant parts are shown for each color combination. The effect is shown as '-' or '+' according to its significance for the three participants from the second phase and one participant from the first phase. For each participant, plot numbers from Appendices D and E are defined and for each participant the differences between background pairs and significances are mentioned.