THE IMPACT OF PERCEPTUAL ORGANIZATION ON THE LIMITS OF BINOCULAR FUSION

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Abstract

As a consequence of the separation of the two eyes in the head, the images of objects projected onto the two retinas are in different positions, called binocular disparity. The brain uses this positional information to represent the 3D layout or depth in a scene, a process called stereopsis. The two monocular half-images of objects will be integrated and seen as single if the binocular disparity is within Panum's fusional area. Objects with disparities beyond this region will be seen as double. There are likely many factors which influence the perception of diplopia, including cognition (i.e., attention or suppression) or low-level object features (i.e., size). This thesis evaluates the proposal that higher-order visual processing, specifically grouping through uniform connectedness, extends the fusion range and thus diminishes the perception of diplopia. To this end, in a series of experiments, I presented single isolated elements, pairs of isolated and connected elements, and elements with varying levels of connectedness. Taken together, the results show that connecting elements elevates diplopia thresholds. This result is consistent with both the impact of perceptual organization and the use of larger receptive fields to process the disparity of the object. These two possibilities are discussed along with future experiments designed to distinguish between these accounts.

Table of Contents

Abstract ii

Table of Contents iii

List of Figures vi

Chapter One: Introduction 1

Stereopsis and Binocular Single Vision 1

Panum's Fusional Area and Diplopia Thresholds 2

Diplopia Thresholds and Stimulus Duration 3

Diplopia Thresholds, Hysteresis, and Stimulus Properties 4

The Disparity Gradient Limit 4

Diplopia Thresholds and Perceptual Organization 5

Current Research 8

Chapter Two: General Methods 9

Observers 9

Apparatus 9

Chapter Three: Experiment 1 10

Introduction 10

Observers 10

Stimuli 10

Procedure 12

Results and Discussion 12

Chapter Four: Experiment 2 15

Introduction 15

Observers 15

Stimuli 15

Procedure 19

Experiment 2a Results and Discussion 20

Experiment 2b Introduction 21

Experiment 2b Observers 22
Experiment 2b Procedure 22
Experiment 2b Results and Discussion 22
Experiment 2c Introduction 23
Experiment 2c Observers 24
Experiment 2c Procedure 24
Experiment 2c Results and Discussion 25
Chapter Five: Experiment 3 27
Introduction 27
Observers 27
Procedure 27
Results and Discussion 28
Chapter Six: Experiment 4 31
Introduction 31
Observers 31
Procedure 32
Results and Discussion 32
Chapter Seven: Experiment 5 35
Introduction 35
Observers 36
Procedure 36
Results and Discussion 37
Chapter Eight: General Discussion 40
Summary 40
The Size-Disparity Correlation 41
Individual Differences 43
Future Directions 43
Considerations 46

Conclusion 47

References 48

List of Figures

Figure 1. An illustration of binocular viewing geometry after Ogle (1952, 1964) is shown here. .2
Figure 2. An illustration of the disparity gradient limit after Burt and Julesz (1980a) is shown here.....5
Figure 3. An illustration of uniform connectedness from Palmer and Rock (1994) is shown here.8
Figure 4. This stereopair illustrates fused (a) and diplopic (b) stimuli, arranged for cross-fusion. 11
Figure 5. An illustration of reference frame (present at all times) and fixation cross (present between trials) is shown here.....11
Figure 6. Three psychometric functions corresponding to stimuli with disparity presented above (light blue) and below (dark blue) fixation, and the average (navy blue) of both positions, obtained from a representative observer's data in Experiment 1, are shown here. 13
Figure 7. The average critical separation limit for fusion at a given disparity for isolated elements above and below fixation, and the average are shown here (N = 20).....14
Figure 8. Stereopairs illustrated here show examples of the isolated ((a) and (c)) and connected ((b) and (d)) stimuli, arranged for cross-fusion. 17
Figure 9. An illustration of the isolated elements as seen by the observer is shown here.....18
Figure 10. An illustration of a random noise outer reference frame (present at all times) and random noise inner frame to help with fixation is shown here.....19
Figure 11. The average diplopia thresholds for isolated and connected elements in Experiment 2a are shown here (N = 20). 21
Figure 12. The average diplopia thresholds for isolated and connected elements in Experiment 2b are shown here (N = 17). 23
Figure 13. The average diplopia thresholds for the isolated and connected element conditions in Experiment 2c are shown here (N = 19).....25
Figure 14. The average diplopia thresholds for the stimulus durations used in the isolated and connected element conditions in Experiment 3 are shown here (N = 16). 29
Figure 15. Illustration of five stimuli configurations with increasing levels of connectedness. ...31
Figure 16. Average diplopia thresholds for elements ranging in levels of connectedness from isolated to fully connected in Experiment 4 are shown here (N = 18). 33

Figure 17. Illustration of five stimuli configurations with increasing levels of connectedness and equivalent number of elements. 36
Figure 18. The average diplopia thresholds for elements ranging in levels of connectedness from isolated to fully connected in Experiment 5 are shown here (N = 19). 38
Figure 19. Stimuli for use in a connectedness rating experiment with all element configurations used in Experiments 1-5. 44
Figure 20. Illustration of five conditions where I manipulate grouping by adding small (b), intermediate (c) and large (d) misalignments of element pairs. Here (f) and (e) show connected elements at horizontal and angled orientations, respectively. 45
Figure 21. The variances associated with the diplopia thresholds obtained using isolated (light blue) and connected (dark blue) conditions in all experiments are shown here. 47

Chapter One: Introduction

Stereopsis and Binocular Single Vision

Two different images of the world are projected onto each retina due to the horizontally separated eyes in the head. Images of objects positioned in the same depth plane are projected onto corresponding points on the retinas, and the objects are seen as single. The horopter is the region in space that consists of all the points whose images project onto corresponding points on both retinas, for a given binocular fixation point (Howard & Rogers, 2012). Images of objects separated in depth from the fixation point project to different locations, or non-corresponding points, on the retina. The brain uses the information from the difference in image positions on the retinas (i.e., binocular disparity) to compute the relative depth between an object and the fixation location, a process called stereopsis (Wheatstone, 1838, as cited in Howard & Rogers, 2012). Even though the retinal images of objects with disparity fall on non-corresponding points on the retinas, the percept of the world is often fused, or single. Objects will be seen as fused over a range of non-zero disparities. The region in space representing the range of disparities wherein single vision is possible is known as Panum's fusional area (Panum, 1858 as cited in Howard & Rogers, 2012)). An illustration of binocular viewing geometry (including the horopter, and corresponding and non-corresponding points) is shown in Figure 1.

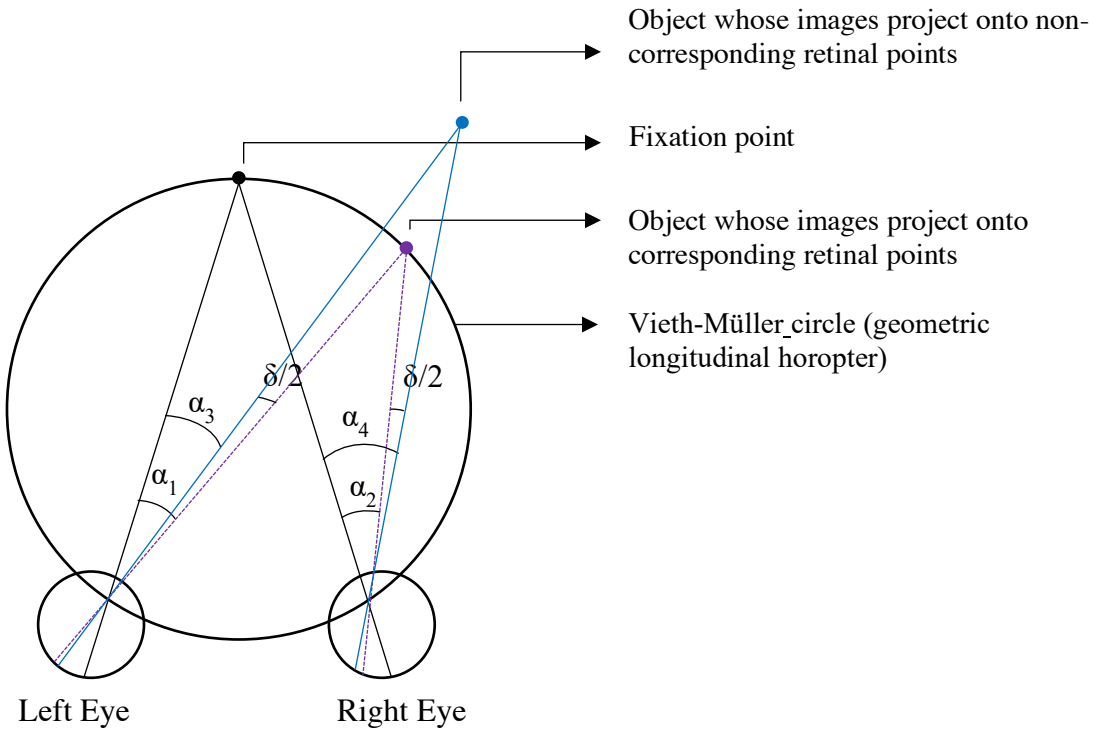

Figure 1. An illustration of binocular viewing geometry after Ogle (1952,1964) is shown here. A fixation point (black) and point in space whose images project onto corresponding points on the retina (purple) are on the geometric horopter. A point in space whose images project onto non-corresponding points on the retina (blue) is off the horopter at a given uncrossed disparity (δ) applied symmetrically around the point (purple) on the horopter. The two visual angles α_1 and α_2 are equivalent; the images projected onto corresponding points on the retinas (through the nodal points of the eyes) are the same distances from the fovea, by definition. The visual angles α_3 and α_4 subtended by the object with disparity (blue) are not equivalent, by definition.

Elements appear double, or diplopic, when the magnitude of disparity between the two retinal images exceeds a threshold value (Mitchell, 1966b; Braddick, 1979). This disparity value is referred to as the diplopia threshold, or the fusional limit.

Panum's Fusional Area and Diplopia Thresholds

As noted above, Panum's fusional area is the region of space for a given fixation point, within which objects with disparity will appear fused. Because it consists of the total range of fusible disparities, the area is the sum of crossed and uncrossed horizontal disparity thresholds for fusion (or superior and inferior thresholds for vertical disparities) (Mitchell, 1966a). In his review, Mitchell (1966a) highlights the confusion around the definition of the fusional limit reported in the literature. Thresholds may be quoted as "Panum's fusional area," but in actuality signify the limiting horizontal disparity for fusion in one disparity direction, or the average fusional limit of both directions. In such cases, these reports are signed diplopia thresholds, rather than the total Panum's area. To clarify, he converted reports of Panum's area to diplopia thresholds (or fusional limits). He noted that diplopia thresholds vary at, and near, the fovea across studies, depending on a number of factors including the stimulus type, exposure duration, and observers' experience.

Diplopia Thresholds and Stimulus Duration

Studies of Panum's fusional area published before Mitchell's review often included unlimited viewing times. For example, Ames and Ogle (1932) found small fusional limits of 5.59 of arc using unlimited viewing time. In another study, Ogle (1952) obtained slightly smaller limits (4 minutes of arc) using a shorter duration (200ms). Mitchell (1966a) hypothesized that the variability in the reported sizes of Panum's fusional area may have been due to fusional eye movements, which were possible given continuous viewing time. Therefore, in a subsequent paper, he measured diplopia thresholds at the fovea in front of and behind fixation for line stimuli presented at a 120ms exposure duration, which is less than the latency period for vergence eye movements (as Mitchell references Ginsborg (1953)). His results showed the average size of Panum's fusional area was 16.9 minutes of arc (a diplopia threshold of 8.45 minutes of arc). There was no significant change in diplopia thresholds when exposure time was decreased to 14ms (Mitchell, 1966b). In another study, he found smaller thresholds of 4.5 minutes of arc with an exposure duration of 80ms (Mitchell, 1966a). Similar to Mitchell (1966b), Palmer (1961) showed no significant change in fusional limits when exposure duration ranged from 10 to 170ms (14.63 and 12 minutes of arc, respectively), which is reasonable given that these durations are less than the time needed to initiate a change in vergence, by some estimates

(Westheimer & Mitchell, 1956). Further, both Palmer and Mitchell showed low inter-observer variability, and similar values with repeated measurement when exposure durations were below the latency period for fusional eye movements. Diplopia thresholds of a similar magnitude measured by Palmer (1961) have also been found with a limited viewing time (Crone & Leuridan, 1973b). Others have argued that diplopia thresholds obtained using continuous and limited viewing time are not significantly different (Duwaer & Van den Brink, 1981b).

Diplopia Thresholds, Hysteresis, and Stimulus Properties

Additional experimental factors impact diplopia thresholds (and Panum's fusional area), including the criterion for fusion and diplopia adopted by the observer (Duwaer & Van den Brink, 1981b; Heckmann & Schor, 1989; Grove et al., 2014). Further, diplopia thresholds exhibit hysteresis (Fender & Julesz, 1967; Piantanida, 1986; Diner & Fender, 1987; Erkelens, 1988). That is, the disparity at which initially diplopic targets regain fusion with slowly decreasing disparity (re-fusion limit) is smaller than the disparity at which initially fused targets appear diplopic (fusion limit) by increasing disparity. Typically, this is taken into account when measuring diplopia thresholds (defined as the average of the fusion and refusion limits) when using the method of adjustment or limits (Howard & Rogers, 2012). Additionally, diplopia thresholds increased using full-field random dot stereograms compared to isolated lines (Boman & Kertesz, 1985). Further, fusion limits have also been shown to increase with increasing target size (Siegel & Duncan, 1960; Ono et al., 1977; Kertesz, 1981; Boman & Kertesz, 1985), and thresholds measured using a central fixation point increase when test stimuli are presented in the periphery (Ogle, 1964; Crone & Leuridan, 1973a, 1973b; Hampton & Kertesz, 1983; Harrold & Grove, 2019).

The Disparity Gradient Limit

In addition to varying with eccentricity, diplopia thresholds are also impacted by the spatial layout of the stimuli, and in particular, the proximity (or separation) of the fixated elements and elements with disparity (Tyler, 1973; Tyler, 1975). Braddick (1979) found that reports of diplopia increased as the monocular horizontal separation of bar elements decreased at

a constant disparity (within Panum's fusional area). Further, many researchers have measured Panum's fusional area as a function of disparity and distance between the fixated and test elements (separation), termed "peripheral angle" (Ogle, 1952, 1964) or lateral "eccentricity" (Palmer, 1961; Crone & Leuridan, 1973b; Harrold & Grove, 2015, 2019), and found that diplopia thresholds increased as separation increased. It is possible to combine these factors (disparity and separation) to describe the disparity gradient, that is, the difference in the relative disparity of the elements divided by their separation (Julesz, 1980a,b; Krol & van de Grind, 1982). The *disparity gradient limit* is the ratio at which simultaneous fusion of the element with disparity and the fixated element is not possible (Burt & Julesz, 1980a,b) (see Figure 2). A gradient above this critical value will result in the perception of diplopia.

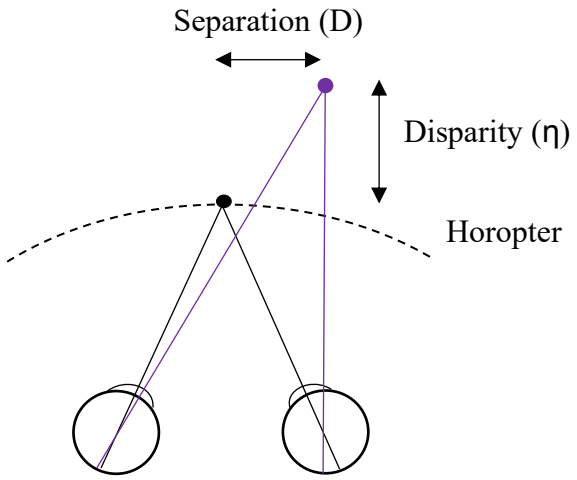

Figure 2. An illustration of the disparity gradient limit after Burt and Julesz (1980a) is shown here. The limit is ratio of disparity to 2D separation (η/D) at which fusion of both the fixated (black) and element with disparity (purple) is not possible.

Diplopia Thresholds and Perceptual Organization

As outlined above, there are many stimulus attributes that influence when objects are perceived as fused or diplopic (i.e., amount of disparity, stimulus size, viewing time). Generally, these stimulus attributes are considered low-level. That is, they correspond to properties that are known to be encoded by disparity tuned neurons early in the visual processing stream (i.e., V1 and V2) (Cumming & Parker, 1997; Groen et al., 2017). Cells in area V2 have been shown to be

sensitive to relative disparities (Cumming & Parker, 1999; Cumming et al., 2002; Thomas et al., 2002; Neri et al., 2004), and neurons in later processing areas (i.e., medial superior temporal (MST), V3, V4 and V5 extrastriate areas) have been shown to encode relative disparity as well as 3D object shape (Eifuku & Wurtz, 1999; Tsao et al., 2003; Krug & Parker, 2011; Uka & DeAngelis, 2006; Umeda et al., 2007).

Understanding the factors that limit fusion is important for understanding object perception in the natural environment, where clutter and complexity create steep disparity gradients throughout the field of view. If the disparity gradient limit sets a low-level constraint on fusion, then objects which exceed this limit should appear diplopic. Diplopia produced by objects with disparities outside Panum's fusional area should constantly occur. There may be multiple factors that contribute to the perception of diplopia and fusion in the natural environment. It is possible that we do in fact see diplopia, though we do not attend to it, and so, we do not notice it. It is well established that attention influences detection of changes seen in natural scenes (Rensink, 2002; Hollingworth, 2003; Hollingworth & Henderson, 2002). For example, change detection improves when changes are semantically or physically imperative to the scene (Rensink et al., 1997). Further, it has been proposed that the visual system simply avoids or continually supresses diplopia (Gonzalez & Perez, 1998), such as in extreme cases like strabismus or amblyopia in which the brain supresses one eye's view to maintain a single coherent world. However, how this takes place in the visual system is unknown (Gonzalez & Perez, 1998). Additionally, given that reliable depth information is obtained from disparities that produce double vision (Ogle, 1952; Westheimer & Tanzman, 1956; Blakemore, 1970), suppression as a solution to naturally occurring diplopia under typical viewing conditions is not a viable option.

Another possible factor contributing to diplopia in complex natural scenes is that the disparity gradient limit is not a fixed value based solely on the relationship between disparity and 2D separation (as argued by Burt and Julesz (1982)) but changes depending on the nature of the stimulus elements. Prazdny (1985) used stereopairs arranged in vertical columns, like Burt and Julesz (1980b), but repeated over a large area. He found that increasing the dissimilarity of interacting elements pairs (by size and contrast polarity) elevated the disparity gradient limit to near 2. This value has been shown geometrically to be the upper disparity gradient limit (Pollard

et al., 1985; Trivedi & Lloyd, 1985; Pollard et al., 1990), though the limit has been empirically measured as 1 by Burt and Julesz (1980a,b). Prazdny's results suggest that fusion is not simply due to the disparity gradient, but instead that the visual system is influenced by the configuration and similarity of the elements (Braddick, 1979; Prazdny, 1985). Further, it has been shown that, though not a perceptual measure, cyclofusional amplitudes increased when stimuli consisted of many randomly segmented horizontal lines (Kertesz, 1972, 1973a,b), suggesting that the size of Panum's fusional area is influenced by stimulus complexity.

Studies of fusion limits have tended to include isolated, fine, black lines (Volkmann, 1859 as cited in Helmholtz, 1962), threads (Fischer, 1924 as cited in Ames & Ogle, 1932), wires (Ames & Ogle, 1932; Ames, et al., 1932), needles (Ogle, 1952), thin rods (Ogle, 1964), simple dot targets (Siegel & Duncan, 1960; Palmer, 1961), lines or bars (presented on a stereoscope or in real space) (Mitchell, 1966a,b; Braddick, 1979; Crone & Leuridan, 1973b; Duwaer & Van den Brink, 1981b; Grove et al., 2014; Harrold & Grove, 2019) or as element arrays (Prazdny, 1985). However, such stimuli rarely occur in the natural world; rather, the visual environment consists of overlapping objects and continuous surfaces. It is possible that the process of perceptual grouping, in addition to organizing the visual scene into coherent objects, plays a role in how and when we perceive diplopia. There is considerable evidence of the impact of mid-level grouping operations on "low-level" disparity processing. For example, the coherence of line fragments connected to form rectangle or triangle figures influences perceived relative depth (Kopfermann, 1930, as cited in Deas & Wilcox, 2014). Stereoacuity is degraded when segmented parallel lines are connected to form continuous rectangular contours (McKee, 1983; Mitchison & Westheimer, 1984). Furthermore, perceived depth magnitude is reduced due to perceptual grouping of line or dot stimuli (Deas & Wilcox, 2014, 2015). Perceptual grouping has also been identified as the cause of degraded depth discrimination in stimuli that are well within Panum's fusional area (Wilcox et al., 2017). These studies indicate that higher-level processing mechanisms (i.e., perceptual organization) influence stereoscopic depth perception. In this thesis, I suggest that perceptual grouping through connectedness may also impact diplopia thresholds (Figure 3). The connectedness manipulation I proposed would cause the elements to be perceived as coherent single objects, which would impact perceiving diplopia.

The main goal of the following series of experiments was to determine whether perceptual grouping by connectedness affects the perception of diplopia; specifically, whether perceptual grouping provides more tolerance to large disparities, thereby increasing the diplopia threshold. In the experiments reported here, I started with simple stimuli to establish baseline performance, and in subsequent experiments manipulated the degree of grouping (via connectedness).

(a) (b)

Figure 3. An illustration of uniform connectedness from Palmer and Rock (1994) is shown here. The dots in (a) and (b) are equally spaced. The dots in (a) appear to be arranged in vertical columns due to grouping via proximity. The dots in (b) are appear as horizontal pairs due to grouping via connectedness.

Current Research

In the series of experiments reported here (Experiments 2 to 5), I measured the diplopia thresholds with connected and isolated elements; I predicted that connectedness would enable fusion at higher disparities, thereby diminishing the perception of diplopia. That is, diplopia thresholds increase in connected compared to isolated elements. In Experiment 1, I established measures of limiting separation for fusion at a constant disparity for single isolated dot elements. In Experiments 2a-c, I investigated the impact of grouping via connectedness on diplopia thresholds for pairs of the dot elements used in Experiment 1. Further, Experiment 3 assessed the potential impact of vergence eye movements on diplopia thresholds. In this experiment, by reducing the exposure duration, I reduced the opportunity to make vergence eye movements. Experiment 4 further assessed the impact of connectedness by varying the degrees of element connectedness, which I predicted would result in higher diplopia thresholds systematically for greater levels of connectedness. Finally, in Experiment 5, I attempted to decoupled stimulus size and the connectedness manipulation by changing the configurations of the elements.

Chapter Two: General Methods

Observers

Observers were recruited from the York University Undergraduate Research Participant Pool (URPP) and were naïve to the purposes of the experiments. A total of 124 observers between ages of approximately 18 to 24 participated in the experiments. They had no prior experience participating in stereoscopic, psychophysical experiments. Observers in each experiment were independent. Information regarding age and gender was not collected. Observers were screened for stereoacuity using the Randot™ test, with an inclusion criterion of at least 40 arcseconds. All had self-reported normal or corrected-to-normal visual acuity and provided written informed consent. The research protocol was approved by the York University Human Participant Research Committee.

Apparatus

Stimuli in all experiments were presented on a mirror stereoscope using the Psychtoolbox (Brainard, 1997; Pelli, 1997) package for MATLAB™. For all experiments except Experiment 1, the displays were two HP Z24X Display Dream Colour Monitors, with peak luminance of 126 cd/m^2. The monitor resolution was 1920x1080 pixels, with a refresh rate of 60 Hz. The computer was an HP Z440 using Windows 10 operating system. The viewing distance was 45 cm, resulting in one pixel subtending 2.05 minutes of arc. Responses were made using a keyboard.

Experiment 1 was conducted on a similar mirror stereoscope. The computer was a Mac running OSX 10.2, and stimuli were displayed on two Dell U2414M displays, with peak luminance of 126 cd/m^2. The resolution was 1920x1200, and the refresh rate was 60 Hz. The viewing distance was 74 cm, so that one pixel subtended 1.25 minutes of arc. Responses were collected from a gamepad unit.

For both stereoscopes, the display screens were parallel to each other and were matched for luminance, spatially calibrated, and aligned prior to testing. The stimuli were viewed through front-silvered mirrors oriented at 90°. The observer's head was stabilized using a chinrest, and the experiment was conducted in a darkened room.

Chapter Three: Experiment 1

Introduction

As mentioned in the General Introduction, the focus of the thesis is the perception of diplopia. The aim of Experiment 1 was to explore the diplopia threshold for single isolated elements under these viewing conditions. One of the means of manipulating the fusion limit is to vary the lateral separation of the elements. In the first experiment, the elements with disparity were presented above or below a central fixation point, similar to the arrangement used in the literature on diplopia thresholds measured at vertical elevations in the visual field (Duwaer & Van den Brink, 1981b; Harrold & Grove, 2015), and akin to a vertical disparity gradient limit in Burt and Julesz's demonstration. Experiment 1 served as a guide for choosing parameters for subsequent experiments; for instance, the fixed separation used in later experiments was informed by the separation manipulation used here.

Observers

Twenty-two observers participated in Experiment 1. None had prior experience with psychophysical, stereoscopic tasks, and all met the inclusion criteria described in the General Methods Section.

Stimuli

The stimuli consisted of a pair of white (95.11 cd/m^2) dots (11.24 arcmin in diameter), with a Michelson contrast of 73%, presented to each eye stereoscopically. One dot of the pair (the fixated element) was presented at the centre of each screen. The other was presented at a range of separations within the field of view, with a crossed disparity of 25 minutes of arc.

The element with disparity was presented randomly either above or below the centre dot to reduce anticipatory eye movements. Stimulus duration was limited to 200ms to limit vergence eye movements and suppression (Westheimer & Mitchell, 1956). Figure 4 provides an illustration of the stimuli as a stereopair.

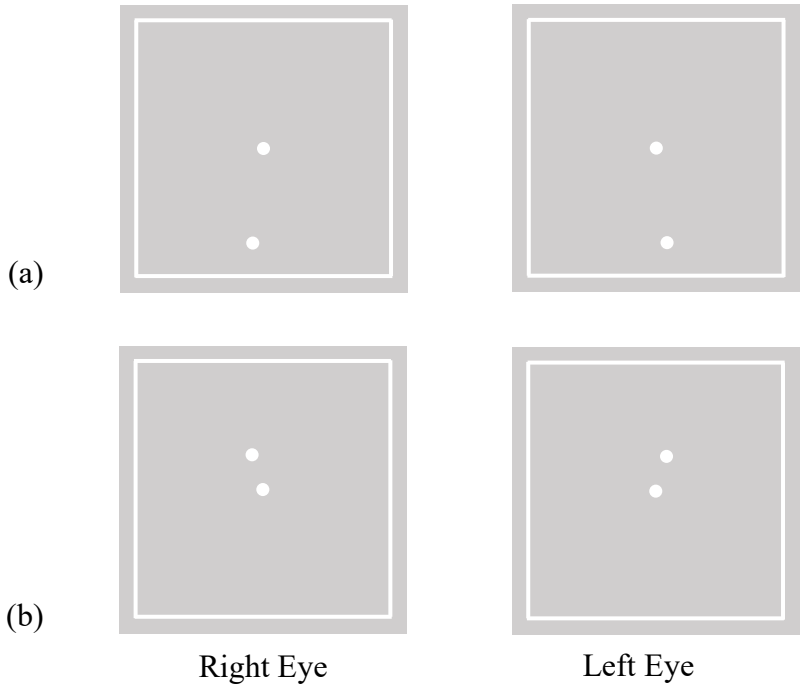

Figure 4. This stereopair illustrates fused (a) and diplopic (b) stimuli, arranged for cross-fusion. In (a), both of the dots appear fused simultaneously. In (b), this is not possible, so when the central dot is fused, the dot above it appears diplopic and vice versa.

Between trials, a fixation cross consisting of nonius lines of equal length was presented at the centre of the screen. A binocular reference frame was always present (Figure 5).

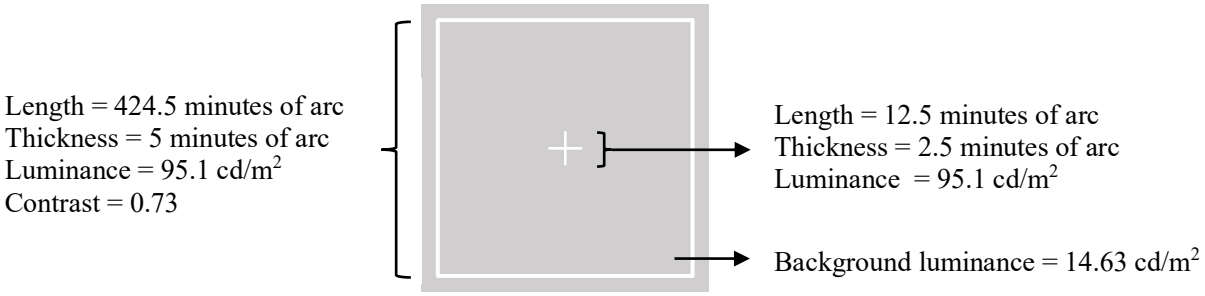

Figure 5. An illustration of reference frame (present at all times) and fixation cross (present between trials) is shown here.

Procedure

In Experiment 1, I measured the critical separation at which diplopia just occurred for single isolated elements, by varying the element separation, while holding the crossed disparity constant at 25 minutes of arc. A forced-choice method of constant stimuli was used, with 9 separations spanning the fusion range. The range was determined for each observer in pilot trials prior to testing.

On a given trial, the observer was instructed to fixate on the dot at the centre and indicate whether the target element appeared single (2 dots) or double (more than 2 dots) using a gamepad. The observers were instructed to ensure the fixation cross appeared aligned between stimuli presentations. Each separation was tested 20 times for a total of 180 trials. A session took approximately 7 minutes, however multiple sessions were sometimes necessary to find the correct range of separations for each observer; in such cases observers were given rest breaks.

Results and Discussion

The proportion of "fused" responses was plotted as a function of separation for each observer. The data was fit with a cumulative normal function, and the 50% point was taken as the critical separation for diplopia at the test disparity. Then a bootstrap procedure was performed to obtain a measure of accuracy (via a 95% confidence interval) of the parameter estimates (see Figure 6).

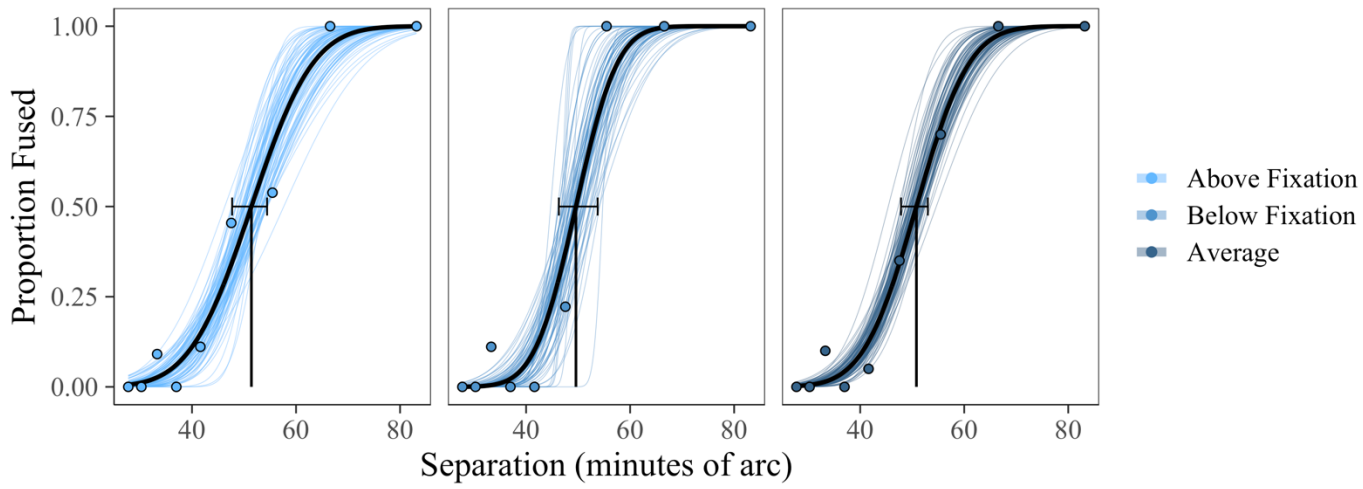

Figure 6. Three psychometric functions corresponding to stimuli with disparity presented above (light blue) and below (dark blue) fixation, and the average (navy blue) of both positions, obtained from a representative observer's data in Experiment 1, are shown here. The abscissa shows the range of separations, and the ordinate shows the proportion of trials the observer responded "fused." Thin lines surrounding the sigmoidal curves (black) represent bootstrapped psychometric functions. The critical separation for diplopia is indicated on each plot (vertical line). Error bars represent 95% confidence intervals for the parameter estimates.

Outlier cut-off values were determined using the interquartile range multiplied by 1.5 added to the third quartile and subtracted from the first (Tukey, 1977). Two observers were identified as outliers and removed from the group of 22 participants. The average critical separation of the 20 observers is plotted in Figure 7. As expected, there appeared to be no effect of stimulus location. This was confirmed using a paired samples t-test, $t(19) = -0.13$, $p = 0.90$, $CI_{0.95} = [-8.86, 7.81]$; $d = 0.030$, $CI_{0.95} = [-4.48, 0.42]$.

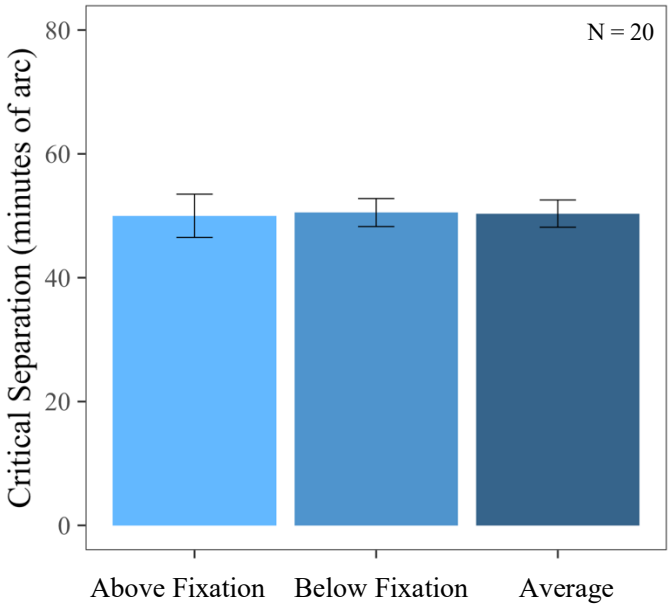

Figure 7. The average critical separation limit for fusion at a given disparity for isolated elements above and below fixation, and the average are shown here (N = 20). Error bars show ± one standard error of the mean.

I found the limiting separation (50 minutes of arc) for fusion at a modest disparity (25 minutes of arc) for simple isolated elements. This experiment served as a guide for expected thresholds in subsequent experiments (2-5) using similar scale stimuli and viewing conditions.

Chapter Four: Experiment 2

Introduction

Experiment 2 investigated the impact of perceptual grouping on diplopia thresholds by pairing and connecting the single elements used in Experiment 1. I hypothesized that grouping elements to form "objects" would expand the fusional range, resulting in higher diplopia thresholds.

Observers

Twenty-two observers participated in Experiment 2a. None had prior experience with psychophysical, stereoscopic tasks, and all met the inclusion criteria described in the General Methods Section.

Stimuli

As in Experiment 1, stimuli were pairs of dots (6.2 minutes of arc in diameter in Experiment 2a, and 8.2 minutes of arc in all subsequent experiments) presented to each eye stereoscopically. There were two conditions: isolated and connected elements (see Figure 8). In the isolated elements condition, three pairs of dots were presented. Observers fixated on the central pair of dots, and the pairs of dots with disparity were presented above and below fixation simultaneously. The latter elements were presented with randomized opposing disparity directions to balance the vergence demand and help avoid response bias. Because both crossed and uncrossed disparities were presented, I did not measure diplopia thresholds in each direction separately. In this experiment, the vertical separation of the target elements from the fixated elements was held constant at 61.6 minutes of arc. This value was chosen because it was close to the median of the range of separations used in Experiment 1 and ensured all dot pairs were comfortably within the field of view. The connected elements condition was the same as the isolated elements condition, but horizontal lines (2.05 minutes of arc in width) connected the pairs of dots in a given depth plane. To evaluate possible effects of element visibility, I changed the lightness of the horizontal connecting line, so it either had the same contrast as (Experiment 2a) or lower contrast (32.4 cd/m^2 luminance; 0.29 contrast) than (Experiment 2b) the dots. In all

other experiments (Experiments 2c to 5), line brightness was the same as the dots (123.8 cd/m^2 luminance; 0.75 contrast). In a third experiment (2c), I reduced the exposure duration to 100ms to limit the opportunity for vergence eye movements. See Figure 9 for an illustration of fused isolated stimuli as they appeared in a trial to the observer.

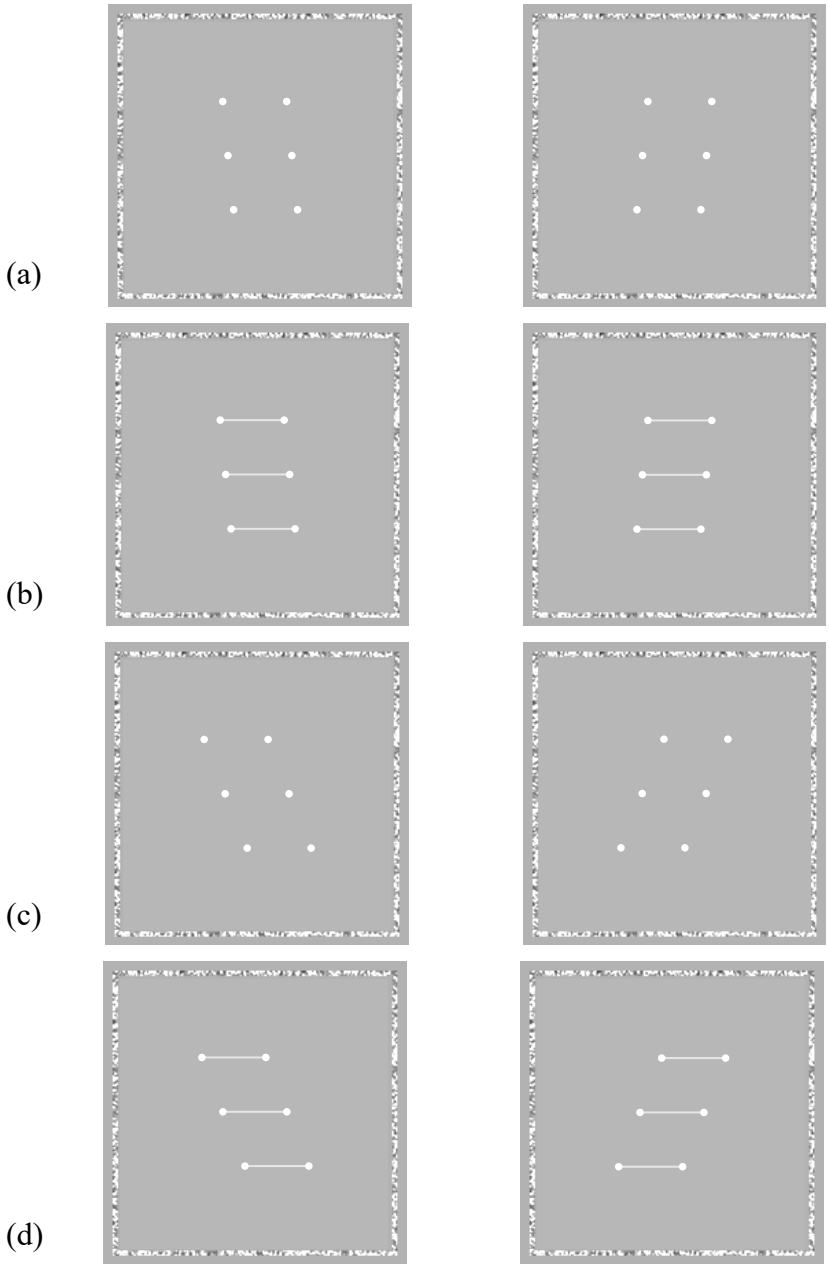

Figure 8. Stereopairs illustrated here show examples of the isolated ((a) and (c)) and connected ((b) and (d)) stimuli, arranged for cross-fusion. For each arrangement, the dot pair in the middle row serves as a fixation stimulus. The top and bottom pairs are presented with uncrossed and crossed disparity, respectively (when free-fused by crossing the eyes). The stereopairs in (a) and (b) have small disparities and appear fused; those in (b) and (d) have large disparities and appear diplopic.

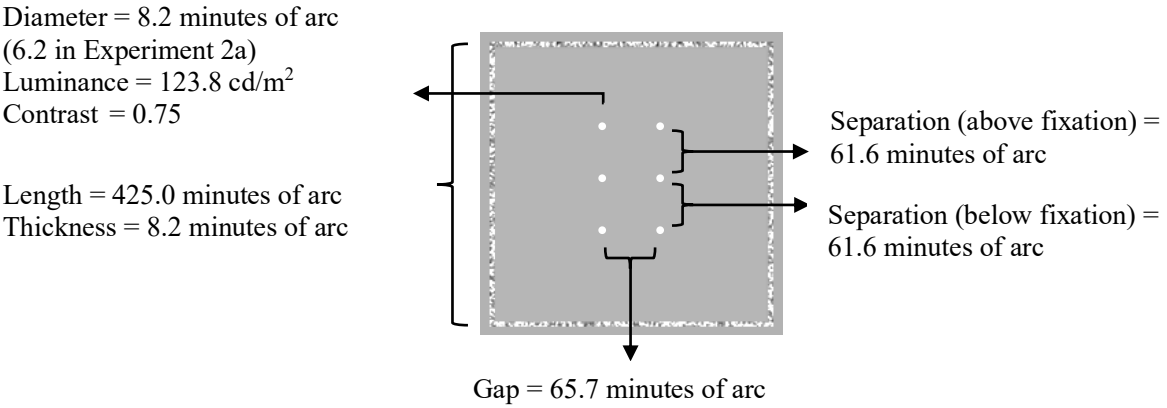

Figure 9. An illustration of the isolated elements as seen by the observer is shown here. The vertical separation (61.6 minutes of arc) was fixed, and a gap (65.7 minutes of arc) was between the elements in the dot pairs. Thus, the gap was also the length of the horizontal line present in the connected elements condition. The random noise outer reference frame, which was present simultaneously as the stimuli, is also shown (described in the next paragraph).

As in Experiment 1, a binocular reference frame surrounded the stimulus area, and was present at all times. However, the frame consisted of random noise instead of a single luminance value, to aid stimulus fusion and help observers maintain binocular fixation. A fixation cross consisting of nonius lines of equal length was presented at the centre of the screen between trials. Because some naïve observers reported difficulties in maintaining fixation, a second random noise frame surrounded the fixation cross. An illustration of the fixation cross and random noise reference frames is presented in Figure 10.

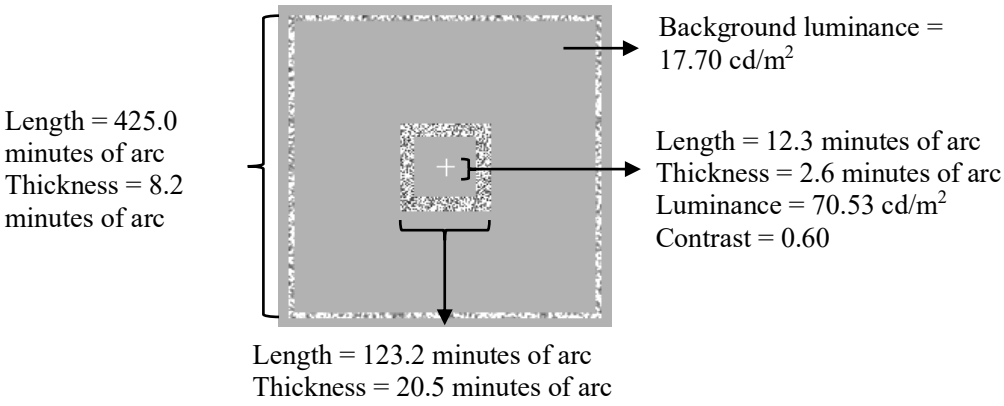

Figure 10. An illustration of a random noise outer reference frame (present at all times) and random noise inner frame to help with fixation is shown here. The inner frame and fixation cross were present between trials but absent when the stimuli were presented.

Procedure

A method of adjustment with an unlimited stimulus duration was used to assess diplopia thresholds. Separation was fixed, and observers changed disparity (from both fused and diplopic starting points) using the arrow keys on the keyboard; the step size was 0.41 minutes of arc. Observers were instructed to either increase the disparity until any of the elements with disparity just appeared double (ascending trials) or decrease the disparity until all elements just appeared single (descending trials), while maintaining fixation on the central pair of elements. When observers inquired whether they could change direction due to uncertainty, they were instructed to avoid making reversals. The diplopia threshold was taken as the mean of the two thresholds (fusion and re-fusion limits, respectively). The starting disparity within either initial fused or diplopic percepts was selected randomly on each trial to avoid biases due to anticipation. A session consisted of random combinations of starting disparity (fused or diplopic) and direction of disparity (upper or lower pair crossed).

After observers made their response, the stimuli disappeared, followed by a 450ms delay before the fixation cross appeared. When observers indicated they were ready to begin a new trial, the fixation cross disappeared, and there was a 750ms delay before the new stimuli appeared, to ensure vergence at the fixation plane before a trial was initiated. The delays were

shortened in Experiment 2c due to observer fatigue and time constraints (450 and 750ms were reduced to 400 and 300ms, respectively). These time delays between the changing elements on the screen were added for observers' comfort, due to the fact that observers were naïve and may not have been used to psychophysical experiments with large changes between diplopic and fused percepts. For this same reason, I presented the isolated and connected element conditions in two separate and counterbalanced blocks, instead of interleaving the two configurations in a single session. A break was provided between blocks, and each block took approximately 15 minutes to complete. Observers were given a practice session consisting of 10 trials to become familiar with the task. There were 160 trials in the entire experimental session (80 trials per condition) in Experiment 2a and b, and 96 total trials in Experiment 2c (48 trials per condition).

Experiment 2a Results and Discussion

Average diplopia thresholds were measured for all observers. Using the exclusion criterion described in Experiment 1, 2 observers of the 22 tested were excluded from the final analysis. The average diplopia thresholds for these 20 observers are plotted in Figure 11. Consistent with my prediction, the thresholds in the connected condition were higher than in the isolated condition. A repeated measures t-test conformed this statistically, with significance interpreted at $p < 0.05$. There was a significant difference between the connected and unconnected conditions, $t(19) = -3.39$, $p = 0.0031$, $CI_{0.95} = [-8.38, -1.99]$; $d = -0.76$, $CI_{0.95} = [-1.27, -0.24]$.

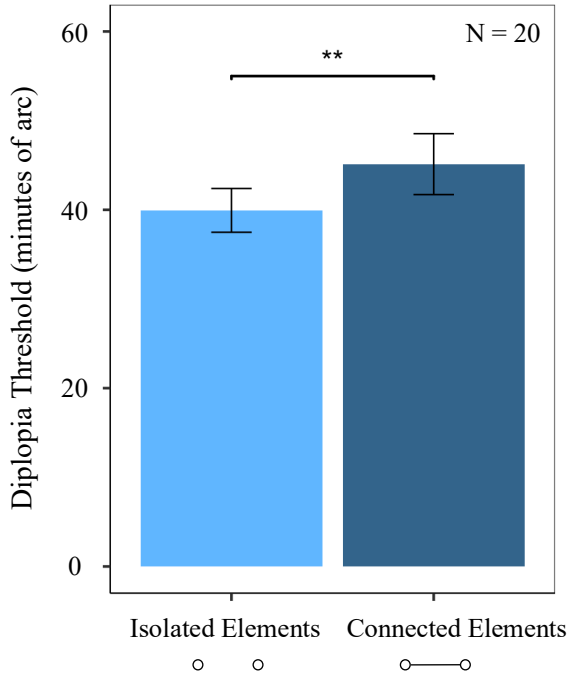

Figure 11. The average diplopia thresholds for isolated and connected elements in Experiment 2a are shown here (N = 20). Error bars show ± one standard error of the mean. The asterisks indicate a significant difference at $p < 0.01$.

I hypothesized that object-based perceptual processing would expand the fusion range, thus diminishing the perception of diplopia. Therefore, I predicted that connected elements would yield higher diplopia thresholds than isolated elements. This prediction was confirmed. However, an alternative explanation for higher thresholds in the connected condition is that the connecting line decreased visibility of the dots, essentially partially masking the edges of the elements, and making it difficult to see diplopia. In Experiment 2b, I increased the contrast between the dot elements and the connecting line, and increased element size slightly, to make the elements more visible.

Experiment 2b Introduction

As outlined above, it is possible that the higher diplopia thresholds in the connected condition was due to observers' ability to resolve the dots when then lines were present. To address this, I increased their size slightly (8.2 minutes of arc in diameter), and I reduced the

luminance of the connecting line. This made the dot pairs more visible so if element visibility was the cause of the difference between the isolated and connected conditions, then this difference should be reduced. However, if the results found in Experiment 2a were due to grouping, the same pattern of results should be seen here.

Experiment 2b Observers

Seventeen observers participated in Experiment 2b. None had prior experience with stereoscopic, psychophysical tasks, and all met the inclusion criteria described in the General Methods Section.

Experiment 2b Procedure

Diplopia thresholds were measured using the method of adjustment as described above.

Experiment 2b Results and Discussion

There were no observers identified as outliers based on statistical exclusion criterion described in Experiment 1. The average diplopia thresholds are plotted in Figure 12. Thresholds were greater when elements were connected. This was confirmed with a repeated measures t-test with statistical significance evaluated at $p < 0.05$. There was a significant difference between the connected and unconnected conditions, $t(16) = -3.09$, $p = 0.0070$, $CI_{0.95} = [-8.34, -1.56]$; $d = -0.75$, $CI_{0.95} = [-1.31, -0.19]$. In both this experiment, and Experiment 2a, diplopia thresholds increased when the elements were connected, irrespective of the contrast of the connecting line and element size.

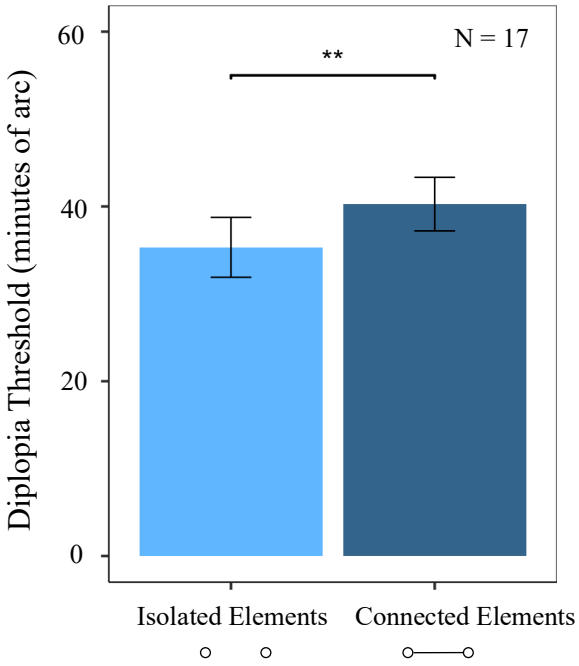

Figure 12. The average diplopia thresholds for isolated and connected elements in Experiment 2b are shown here (N = 17). Error bars represent ± one standard error of the mean. The asterisks indicate a significant difference at $p < 0.01$.

The pattern of results was the same in Experiment 2a and b, which supports the hypothesis that perceptual grouping influences the diplopia threshold. In both Experiments 2a and b, there was a fairly high degree of response variability between observers shown by relatively large standard errors. One potential explanation for this is the extended viewing time. That is, observers may have changed their vergence from one element pair to another, adding some noise to the data. To control for this, in Experiment 2c, stimuli were presented with a viewing time shorter than the latency period required to initiate a change in vergence.

Experiment 2c Introduction

There have been a range of viewing times used in the literature on diplopia thresholds. Stimuli were viewed using either a single brief (i.e., Mitchell (1966a,b)) or continuous (i.e., Ogle (1964) and Harrold and Grove (2015)) viewing time, or viewing time was manipulated in a

single experiment (i.e., Woo (1974), Palmer (1961), Harrold and Grove (2019), and Duwaer and Van den Brink (1981a,b)). Palmer (1961) and Mitchell (1966b) found consistent fusion limits when using limited exposure times. They noted the influence of eye movements in the variability of thresholds. Here, I used a similarly brief presentation time (100ms), which is shorter than the latency period to initiate vergence eye movements (Ginsborg, 1953; Westheimer & Mitchell, 1956; Rashbass & Westheimer, 1961a). Because Experiment 2b confirmed that the diplopia threshold elevation in the connected condition was not due to element visibility, the luminance of the connecting line was the same as the dots (as in Experiment 2a).

Experiment 2c Observers

Twenty-one observers participated in Experiment 2c. As in the previous experiments, none had prior experience with psychophysical, stereoscopic tasks, and all met the inclusion criteria described in the General Methods Section.

Experiment 2c Procedure

The method of adjustment procedure was used here to assess diplopia thresholds. Here however, the viewing time was controlled. At the beginning of the session, the random noise reference frame (continuously present) and the fixation cross and surrounding frame appeared. Observers were instructed to begin the trial when the nonius lines were properly aligned. Then, the fixation cross and frame disappeared, followed by a 400ms delay, and the stimuli were presented for 100ms. Then the stimuli disappeared, followed by another 400ms delay, and the fixation cross and frame appeared. Then observers made their adjustment, and the sequence repeated. When a trial was complete, observers input their response (taken as the fusion or re-fusion limit), followed by a 300ms delay before the fixation cross and frame appeared, indicating a new trial. For observers' comfort, I avoided interleaving conditions, and added pauses between changes on the screen. The conditions were presented in two separate blocks in counterbalanced order, with a break in between blocks. There was a total of 96 trials (48 per condition). The step size was increased to 4.1 minutes of arc due to time constraints. Observers were given two practice sessions consisting of 10 trials each to become familiar with the brief exposure duration.

Experiment 2c Results and Discussion

Average diplopia thresholds were calculated. Of the 21 observers who participated, 2 were excluded from the final analysis based on the outlier criterion described in Experiment 1. The average diplopia thresholds are shown in Figure 13. As in Experiments 2a and b, diplopia thresholds were higher when elements were connected. The significant effect of condition on thresholds was confirmed statistically with a repeated measures t-test, $t(18) = -5.56$, $p < 0.0001$, $CI_{0.95} = [-14.83, -6.70]$; $d = -1.28$, $CI_{0.95} = [-1.90, -.65]$. Here, when the exposure duration was brief, I found a strong effect of element connectedness on diplopia thresholds. As expected, limiting the opportunity for observers to change their eye position reduced variability in the data, shown by lower standard error of the means for both conditions compared to the previous two experiments.

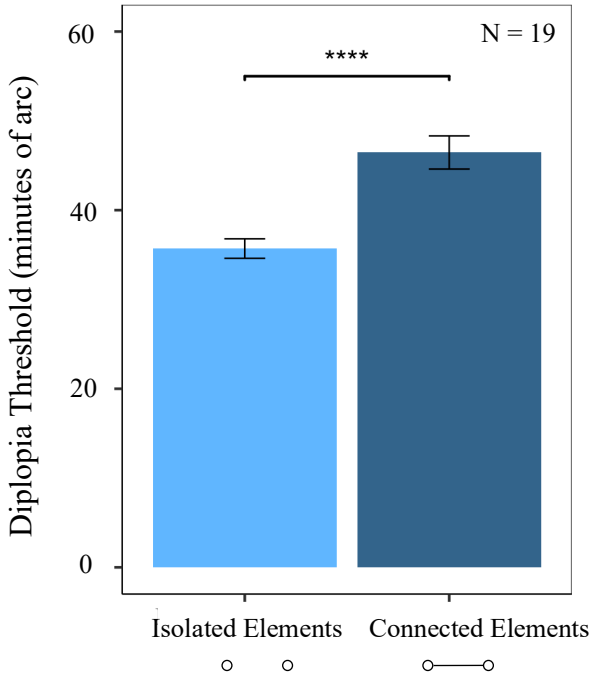

Figure 13. The average diplopia thresholds for the isolated and connected element conditions in Experiment 2c are shown here (N = 19). Error bars represent ± one standard error of the mean. The asterisks indicate a significant difference at $p < 0.0001$.

There was a significant effect of connectedness on diplopia thresholds in Experiments 2a-c; this pattern was consistent for both limited and unlimited viewing times. The effect of connecting the line pairs on diplopia thresholds is not eliminated by changing the visibility of the elements (2b), nor by limiting viewing time (2c). In Experiment 2, I tested only two exposure durations: unlimited vs. 100ms. Due to the mixed effect of viewing times in the literature on diplopia thresholds (Duwaer & Van den Brink, 1981a,b; Mitchell, 1966a), in Experiment 3, I looked at the impact of viewing time in more detail.

Chapter Five: Experiment 3

Introduction

As discussed above, the literature is mixed with respect to the effect of exposure duration on diplopia thresholds. For instance, Palmer (1961) and Mitchell (1966a,b) showed no significant effect of changing viewing time on diplopia thresholds (10-170ms and unlimited). Duwaer and Van den Brink (1981b) showed diplopia thresholds were not significantly higher when exposure duration was brief (160ms) compared to unlimited. In contrast, Woo (1974) showed that diplopia thresholds increase with increasing exposure duration between 5 and 100ms. Some of the differences in the patterns of results seen in these studies may be due to other stimulus attributes (i.e., element size, contrast), or other factors such as attention, cognition, or suppression, which makes it difficult to compare them to my experiments. Given the mixed effects of exposure time, it was also important to verify that the single exposure duration chosen in Experiment 2c was reasonable for the rest of the experiments. Therefore, I examined diplopia thresholds as a function of viewing time in more detail by presenting stimuli at a range of durations.

Observers

Twenty observers participated in Experiment 3. None had prior experience with stereoscopic, psychophysical tasks, and all met the inclusion criteria described in the General Methods Section.

Procedure

In Experiment 3, I used the method of adjustment procedure described in Experiment 2c. However, here, and in Experiments 4 and 5, the selection of ascending vs. descending directions on each trial was randomized, as a result there was the potential for an unequal distribution of trials across direction. The potential impact of this error would be to increase the bias in a given trial, but when averaged across trials would increase the variability between observers. I address the implications of this issue in more detail in the Discussion Section. Here, I used exposure durations less than (70 and 200ms), and greater (350 and 700ms) than, the latency period to

initiate vergence eye movements. With 4 exposure durations, 12 presentations of each exposure, and 2 conditions (connected, unconnected), there were a total of 96 trials. The stimulus durations were presented in random order within a single condition. The two conditions were presented in separate blocks (each 25 minutes) in counterbalanced order. Observers were given two practice sessions consisting of 10 trials each to become familiar with the brief exposure durations.

Results and Discussion

Average diplopia thresholds were computed for 20 observers; 4 observers were removed from the analysis based on the outlier criterion described previously. Diplopia thresholds for the configurations at each stimulus duration are presented in Figure 14. There was no significant change in diplopia thresholds as a function of stimulus duration. This observation was confirmed in a multifactorial repeated measures Analysis of Variance, with significance interpreted at $p < 0.05$, $F(3, 45) = 1.18$, $p = 0.33$, $\eta_G^2 = 0.012$. Thresholds were consistently higher for connected elements. There was a (marginally) significant main effect of the grouping manipulation, $F(1,15) = 4.64$, $p = 0.048$, $\eta_G^2 = 0.077$. There was also no significant interaction between the two variables. Mauchly's test of sphericity was not met, and so a Greenhouse-Geisser correction) was applied to the degrees of freedom for the interaction between condition and stimulus duration, $F(2.03, 30.46) = 1.94$, $p = 0.14$, $\eta_G^2 = 0.0092$.

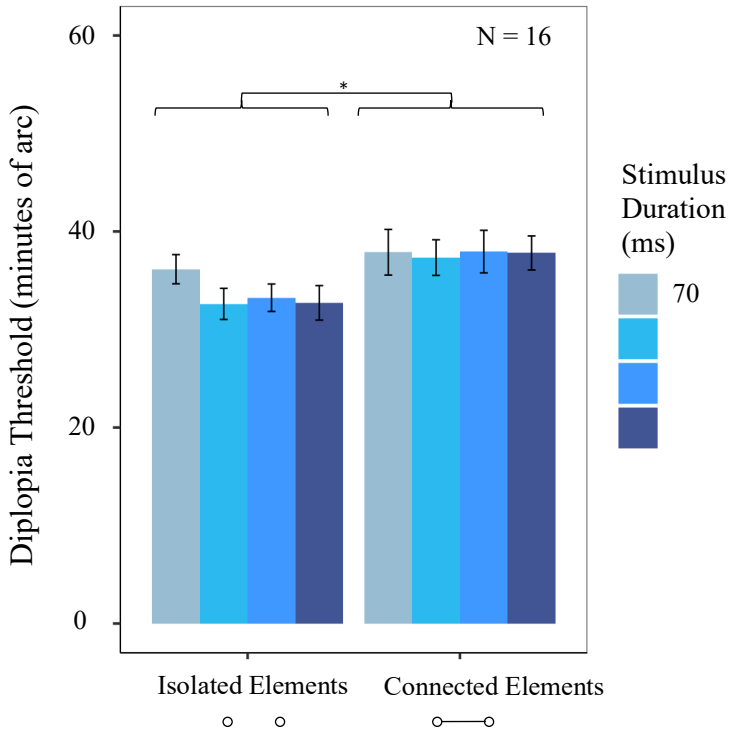

Figure 14. The average diplopia thresholds for the stimulus durations used in the isolated and connected element conditions in Experiment 3 are shown here (N = 16). Error bars represent ± one standard error of the mean. The asterisk indicates a significance interpreted at $p < 0.05$.

This study investigated the impact of vergence eye movements on the diplopia thresholds by manipulating the opportunity to change vergence. While I did not measure eye movements here, it is well established that binocular disparity (particularly large disparities) drives fusional eye movements (Riggs & Niehl, 1960; Rashbass & Westheimer, 1961b; Schor, 1979; Semmlow & Wetzel, 1979; Jones, 1980; Stark et al., 1980), so it is reasonable to assume that in these viewing conditions increasing the exposure duration would result in increased vergence eye movements. Thus, even though observers were instructed to maintain fixation upon the central dot elements, when viewing times are not limited, vergence eye movements are more likely to occur. The results of Experiment 3 confirm that there is little impact of viewing time on the diplopia threshold over this range of exposure durations test (70 to 700ms). While performance was slightly worse at the shortest duration for the isolated element condition, this may simply be due to the observers having difficulties resolving the small dots in such brief intervals.

Experiment 3 examined the influence of viewing time by testing a wide range of durations that encompassed most of those durations used previously. The results replicate those of Mitchell (1966b) and of Palmer (1961) in showing that there is no change in thresholds as a function of stimulus duration. I concluded that the primary impact of limiting vergence eye movements in my study is to reduce variability. Eye movements may simply increase noise in the disparity signal when the images of the elements move on the retina. In subsequent experiments, I used a duration of 100ms which was sufficient to limit vergence eye movements and remain comfortable for observers.

Chapter Six: Experiment 4

Introduction

Experiments 2 and 3 consistently show an increase in the diplopia threshold for connected elements. To this point, I have compared only isolated and fully connected elements. If perceptual grouping is indeed underlying this effect, then I expected thresholds to increase systematically with the degree to which elements are connected to form objects. Thus, in Experiment 4, I tested this prediction by presenting stimuli with different degrees of connectedness (by adding gaps in the centre of the connecting line), as illustrated in Figure 15.

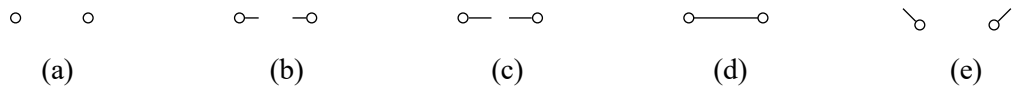

Figure 15. Illustration of five stimuli configurations with increasing levels of connectedness. From left to right, the illustrations show (a) isolated, (b) low connectedness, (c) high connectedness, and (d) full connectedness elements. The final configuration (e) shows disconnected elements with the same figural components as (c).

The degree of connectedness was varied by creating gaps between the elements. For instance, the size of the gaps for the illustrations in Figure 15 (b) and (c) were 35 and 9 minutes of arc, respectively. The line length in the control condition with disconnected lines oriented at 45 degrees (Figure 15 (e)) was the same as that required to create a gap of 22 minutes of arc (midway between (b) and (c)). This configuration was included as a control in which the elements were not connected but had the same configural elements. I predicted that if higher diplopia thresholds were due to the grouping via connectedness principle, the threshold for this condition should have been approximately equal to the isolated element condition. As in Experiment 2c, 3, 5, and here, the connecting lines and the dots were presented at the same luminance value.

Observers

Twenty-two observers participated in Experiment 4. As in all previous experiments, none had prior experience with stereoscopic, psychophysical tasks, and all met the inclusion criteria described in the General Methods Section.

Procedure

The procedure used in Experiment 2c was also used here, with an exposure duration of 100ms. There were 10 repetitions per condition for a total of 50 trials. Again, configurations were not interleaved to avoid the potential eye strain or discomfort caused by large stimuli changes between trials. Instead, the conditions were presented in blocks of random order; each block consisted of the 10 repetitions for each condition. Observers were permitted a break halfway through the experiment, which took approximately 20 minutes to complete. There were two practice sessions consisting of 10 trials each to familiarize observers to the stimuli and become comfortable with the brief viewing time.

Results and Discussion

Average diplopia thresholds were calculated for each condition for 22 observers. Four observers were excluded from the final analysis based on the outlier criterion. Average thresholds obtained from 18 observers for all conditions are plotted in Figure 16. The results show that diplopia thresholds increase as element connectedness increases. This was confirmed with a multi-level repeated measures ANOVA. There was a significant effect of connectedness grouping conditions on diplopia thresholds, $F(4, 56) = 15.64$, $p < 0.0001$, $\eta_G^2 = 0.29$. A pair-wise multiple comparison t-test with a false discovery rate correction was run as a post hoc test, to analyze particular differences in thresholds between levels of element connectedness.

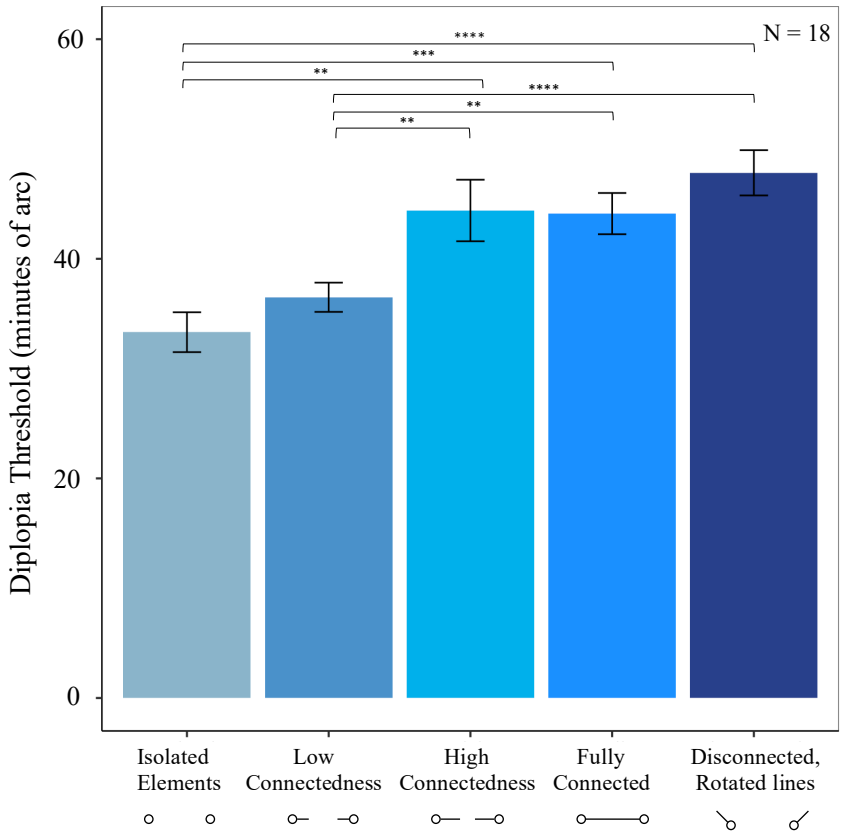

Figure 16. Average diplopia thresholds for elements ranging in levels of connectedness from isolated to fully connected in Experiment 4 are shown here (N = 18). Error bars represent ± one standard error of the mean. Bars above the conditions indicate significant pair-wise differences. Two, three, and four asterisks refer to $p < 0.01$, $p < 0.001$, and $p < 0.0001$, respectively.

Diplopia thresholds increased, as predicted, along with increasing connectedness. Thresholds for the isolated and minimally connected conditions were significantly lower than the high and full connectedness conditions. Interestingly, there was no significant difference between the fully connected and control condition with disconnected rotated lines. If the increase in diplopia thresholds seen in the connected condition was due to the grouping manipulation, I predicted lower thresholds in the control compared to the fully connected conditions. Since this control condition should not be subject to perceptual grouping via connectedness, I also predicted little difference in thresholds between this condition and the isolated or minimally

connected elements. However, these predictions were not confirmed. Thresholds obtained using the control condition were significantly higher than those obtained using both the isolated ($t(56) = -6.76$, $p = 0.000033$, $d = -1.59$) and minimally connected ($t(56) = -6.12$, $p = 0.000056$, $d = -1.44$) elements.

While the elevated diplopia threshold seen in the rotated-element control condition is not predicted by the grouping hypothesis, it is consistent with another low-level phenomenon: the size-disparity correlation. That is, the addition of the lines to the dots effectively increases their size, and so they may stimulate neurons with larger receptive fields. As outlined below, such neurons may encode larger ranges of disparity, and therefore result in higher diplopia thresholds. While I concluded from my experiments to this point that element connectedness caused increases in diplopia thresholds, the experiments performed thus far do not distinguish between these two explanations (i.e., grouping or the size-disparity correlation). Therefore, in Experiment 5, I attempt to decouple connectedness from element size.

Chapter Seven: Experiment 5

Introduction

As mentioned above, it is possible that the size-disparity correlation may explain the elevated diplopia thresholds in Experiment 4. Firstly, neurons in the human visual cortex preferentially respond to stimuli features such as location and orientation (Hubel & Wiesel, 1959, 1962). Neurons with small receptive fields respond to high spatial frequencies and detect fine features (Andrews & Pollen, 1979; Pollen & Ronner, 1983). As a consequence of this property, these neurons encode small disparities; neurons with larger receptive fields that are tuned to broader scales (low spatial frequencies) encode larger disparities (Tyler, 1975; Anzai et al., 1997, 1999; Schor & Wood, 1983; Schor et al., 1984). It is widely believed that disparity selective neurons in early visual areas encode disparity via phase shifts in the receptive field profiles (DeAngelis et al., 1991; Cumming & DeAngelis, 2001). As a result, the maximum disparity a neuron can encode depends on its preferred spatial frequency (Anzai, et al., 1997, 1999). The dependence of the range of disparities a neuron can encode on its preferred spatial frequency (i.e., wide- or narrow- sized stimuli) is termed the size-disparity correlation (DeAngelis et al., 1991; Smallman & MacLeod, 1994; Prince & Eagle, 1999; Prince et al., 2002).

Another means by which binocular disparity is encoded is through the relative position of the neuron's receptive field. It has been argued that position-disparity detectors are more likely to process very large binocular disparities (Edwards & Schor, 1999; Prince et al., 2002; Chen & Qian, 2004), though it has also been shown that position-disparity encoding is more reliable for receptive fields tuned to high spatial frequencies (Anzai et al., 1997, 1999). Disparity selective neurons that rely on position coding will exhibit maximum response when the monocular receptive sub-fields match the size of the stimulus features. Thus, larger stimuli will activate neurons with larger receptive fields. As noted by Anzai et al. (1997, 1999), this property will be reflected in their spatial resolution. However, unlike neurons which use phase coding, there is not as direct a correlation between the size of the receptive field and the preferred disparity. By definition, position-coding means that a given receptive field size can encode a large range of disparities defined by the positional offset between the receptive fields. Therefore, if position coding is used, the impact of stimulus size on the diplopia thresholds should be somewhat

weaker. It is not possible to know if either or both Phase vs. Position coding is used to processes disparity information in the stimuli used here.

In Experiment 4, the connectedness manipulation (increasing the lengths of the lines touching the dots) may have resulted in their stimulation of neurons with larger receptive fields. According to the size-disparity correlation, these neurons would encode larger disparities, and I propose would potentially result in elevated diplopia thresholds. Here, I manipulated connectedness by inserting a line of variable length between dot pairs. To ensure the size of the dot elements was unchanged, the connecting line did not "touch" the dot in any of the intermediate connectedness configurations (see Figure 17). I created similar levels of connectedness as in Experiment 4 with line lengths of 16.8, 34.8, 52.8, and 65.7 minutes of arc, or gaps of 24.5, 15.5, and 6.5 minutes of arc between each element and the connecting line.

(a) (b) (c) (d) (e)

Figure 17. Illustration of five stimuli configurations with increasing levels of connectedness and equivalent number of elements. From left to right, the illustrations show (a) isolated elements (b) minimal, (c) intermediate, (d) high, and (e) full connectedness.

Observers

Twenty-two observers participated in Experiment 5. None had prior experience with stereoscopic, psychophysical tasks, and all met the inclusion criteria established in the General Methods Section.

Procedure

The method of adjustment procedure described in Experiment 2c was also used here. The same stimulus duration (100ms), repetitions per condition (10) and number of trials (50) used in Experiment 4 were applied. Conditions were presented in randomized blocks, with each block consisting of the 10 repetitions. This was done to avoid large stimulus changes between trials which for these naïve observers caused confusion and more variable data. Observers were given

two practice sessions consisting of 10 trials each to become familiar with the stimuli and brief viewing time.

Results and Discussion

Diplopia thresholds were assessed for 22 observers; 3 subjects were excluded from the final analysis based on the outlier criterion described previously. The average diplopia thresholds are shown in Figure 18. Results showed elevated diplopia thresholds as a function of greater element connectedness in the intermediate to fully connected conditions. This observation was confirmed statistically using a repeated measures multi-level Analysis of Variance, with significance interpreted at $p < 0.05$. There was a significant effect of the grouping manipulation on diplopia thresholds, $F(2.61, 47.01) = 10.95$, $p < 0.0001$, $\eta_G^2 = 0.22$. The Mauchly's test of sphericity was significant, so a Greenhouse-Geisser correction was applied to the degrees of freedom. A pair-wise multiple comparison t-test with a false discovery rate correction was run as a post hoc test to analyze differences in thresholds between levels of element connectedness.

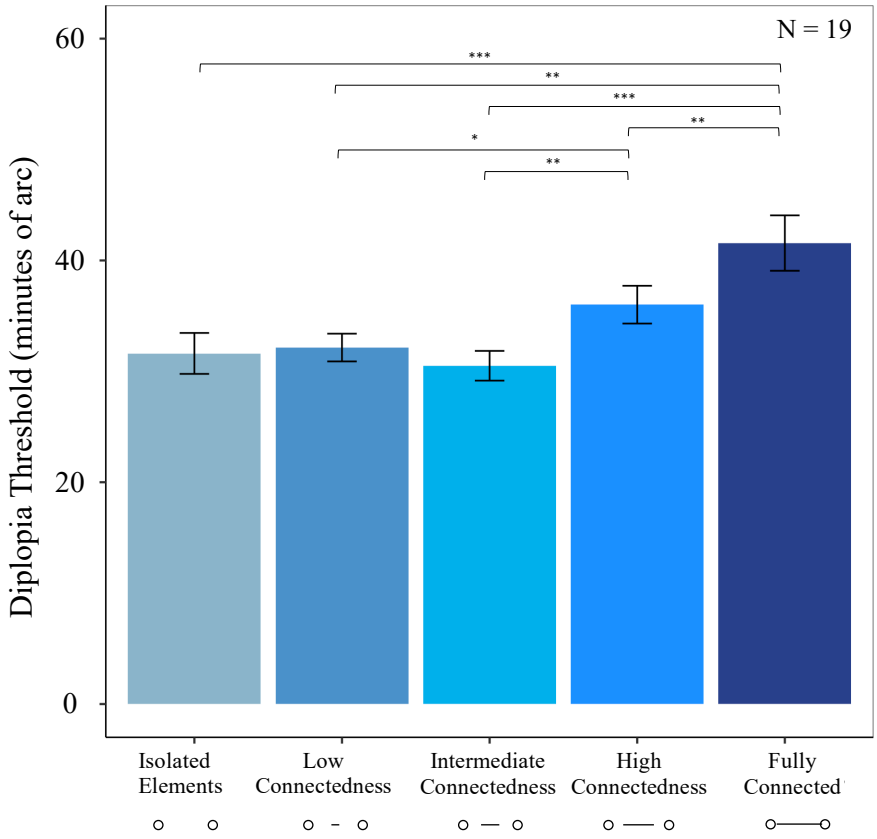

Figure 18. The average diplopia thresholds for elements ranging in levels of connectedness from isolated to fully connected in Experiment 5 are shown here (N = 19). Error bars represent ± one standard error of the mean. The bars above the conditions indicate significant pair-wise differences with a correction for family wise error. One, two, and three asterisks refer to $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

Some of the results of Experiment 5 are also consistent with the presence of the size-disparity correlation. This can be seen in the lack of effect of increasing connectedness in conditions illustrated in Figure 17 (a) (isolated) through (c) (intermediate connected), where the dot elements are isolated and maintained the same size. Further, the difference between these conditions (a)-(c) and the fully connected condition (e), is consistent with the impact of the size-disparity correlation, given that the latter condition should stimulate larger receptive fields.

However, the fact that there is a difference between the condition with the smallest gap (d) and both the intermediate connectedness (c) and fully connected (e) condition is more

consistent with the grouping hypothesis. Further, comparison of these three conditions (Figure 17 (c)-(e)) shows the expected increase in diplopia thresholds with increasing connectedness. It is clear that further research is needed, but my working hypothesis is that both mechanisms (grouping and the size-disparity correlation) are at play and are reflected in these results.

Chapter Eight: General Discussion

Summary

The series of experiments described here investigated the impact of perceptual grouping on the perception of diplopia. The motivation for the experiments was the observation that diplopia should occur in the natural environment because the disparity gradient limit is often exceeded, objects have large disparities outside Panum's fusional area . There may be a number of factors involved in maintaining fusion in such circumstances. It is possible that diplopia does in fact occur, however we do not notice it because we do not attend to it. In doing so, we are able to interact with objects that should appear diplopic and make sense of relative depths in the natural environment. In this thesis, I hypothesized that fusion is not solely due to the relationship between disparity and separation (the disparity gradient), or the magnitude of disparity, but is also influenced by perceptual organization. Measures of fusion limits in the existing literature often used simple isolated stimuli (Ogle, 1964; Palmer, 1961; Mitchell, 1966a), which rarely occur in the real world, where features connect and form objects, clutter occurs, and surfaces overlap. In the experiments outlined in this thesis, I used stimuli consisting of connected elements to approach the complex objects appearing in natural environments. I proposed that grouping via uniform connectedness extends the fusional range.

In Experiment 1, I measured the critical vertical separation at which diplopia just occurred for a given disparity. This experiment illustrated the impact of separation on diplopia (the disparity gradient), and the results guided the fixed separation value used in my subsequent experiments on diplopia thresholds. The isolated elements used in Experiment 1 were then paired and connected with thin horizontal lines in Experiment 2a-c to manipulate grouping. Results showed a significant increase in diplopia thresholds when elements were grouped to form a common object. Then, by limiting exposure duration and limiting the opportunity for vergence eye movements, Experiment 2c reduced variability in responses. In Experiment 3, I tested a range of exposure durations to explore the impact of vergence eye movements on diplopia thresholds in more detail. As expected, there was no significant effect of duration. Experiment 4 assessed whether diplopia thresholds increased with increasing element connectedness by presenting internal lines of different lengths extending from the dot elements. While the results were consistent with my hypothesis, this manipulation may have effectively increased the size of

the dot elements, leading to an increase in diplopia thresholds due to the size-disparity correlation, not to connectedness; the stimuli configurations confounded size and grouping. To disentangle the size-disparity correlation and the grouping manipulation, in Experiment 5, I again investigated the change in diplopia thresholds with varying connectedness by presenting lines of differing lengths but detached from the elements. The results of this study were not definitive. That is, some aspects of the data supported the size-disparity correlation account, while other aspects supported the perceptual grouping hypothesis. I concluded that while perceptual grouping can increase diplopia thresholds, additional experiments are needed to distinguish these effects from low-level explanations such as the size-disparity correlation.

The Size-Disparity Correlation

In the experiments discussed in this thesis, I proposed that the increase in diplopia thresholds for connected elements was due to the effect of perceptual grouping, i.e., a higher order visual process. One could argue that the effect of connecting the elements in Experiment 2 was due to low-level properties of cortical neurons. As described in the Introduction of Experiment 4, the property that the range of disparities a phase-coding neuron can encode is tied to its preferred spatial frequency is termed the size-disparity correlation. Neurons with large or small receptive fields, which respond to large and small stimuli, encode large and small disparities, respectively. In the experiments discussed in this thesis, it is possible that connection of the two isolated elements resulted in stimulation of a single larger receptive field, thereby making the stimulus tolerant to larger disparities (increasing the diplopia threshold). In Experiment 2a-c, elements were connected to form objects by drawing a thin line between the dot elements. This manipulation effectively increased the size of the stimuli, which, according to the preceding logic, may have caused the elevated diplopia thresholds. The literature on the perception of diplopia has shown a relationship between stimulus size and diplopia thresholds. That is, fusional limits increase with increasing target size (Siegel & Duncan, 1960; Tyler, 1973, 1975; Ono et al., 1977; Kertesz, 1981; Boman & Kertesz, 1985). The size-disparity correlation may also explain the increase in thresholds in Experiment 4, where the connecting line extended from the dot stimuli (so the elements became larger and gap between them became smaller), and the control condition where the lines were rotated (so no grouping should have occurred).

However, some of the results from do not appear to be consistent with the size-disparity correlation as the sole explanation for the observed increased thresholds for connected elements. For instance, in Experiment 4, the difference between the results obtained using the element configurations that were almost connected (smallest gap) and the fully connected condition was not significant. The size-disparity correlation hypothesis would predict that the gap between the dot-line segments should have resulted in stimulation of two smaller receptive fields, and therefore reduce the threshold in that condition relative to the fully connected condition. Instead, diplopia thresholds were nearly identical, a result which is consistent with the grouping hypothesis. That is, though there was a gap between the line and the dot, because it was very small, the configuration was seen as a single object. This explained why diplopia thresholds were not significantly different from the fully connected element configuration, as elements in both configurations were perceived as connected objects.

In the experiments discussed here, the assumption is that the disparity information was being encoded by the receptive field size that was optimally activated by the stimulus, therefore matched in size. As such, in Experiment 4, the slight increases in size as the degree of connectedness increases (smaller gaps) would stimulate different sizes receptive fields, and the neurons' responses to those stimuli would be different. However, if fusion/diplopia was encoded by the largest possible scale receptive fields, the output from those neurons would be the same for both the connected and smallest gap conditions (Figure 15 (d) and (c), respectively). That is, neurons tuned to coarse scales or low resolutions would not detect the small gaps in the stimuli features. This may explain the similar thresholds obtained using those two conditions, rather than the presence of grouping. Alternatively, the higher diplopia thresholds found using elements with greater connectedness (and subsequently larger size) in Experiment 4, suggest that the optimal (smaller) scale rather than large scale units were more likely involved in encoding disparity information and signalling loss of fusion. For instance, the significantly higher thresholds found using the stimuli in Figure 15 (c) compared to (b) indicate that small scale receptors encoded the disparity because those neurons were able to detect the change in size of the two configurations. According to this logic, in Experiment 4, there should have been no difference between the low, intermediate, and highly connected element conditions if only the largest scale tuned neurons were involved in signalling diplopia.

In all the configurations in Experiment 5, apart from the fully connected condition, the dots were disconnected from the lines. According to the size-disparity correlation explanation, the small dots should activate the same-sized receptive fields in all conditions, and so the diplopia threshold should not change (except for the fully connected condition). It is true that there is no difference in the diplopia threshold obtained using isolated elements and the two conditions with short connecting lines (low and intermediate). However, diplopia thresholds gradually increase with increasing line length from the intermediate to fully connected condition. It appears that both phenomena, the low-level size-disparity correlation and the mid-level perceptual grouping, serve to increase diplopia thresholds. Further experiments are required to evaluate their individual contributions.

Individual Differences

The fusion limits reported in the existing literature vary considerably from one study to another, however, within study variability is very low. The experiment parameters in this literature tended to consist of very brief exposure durations (less than the latency period for vergence eye movements) with few highly experienced psychophysical observers (Palmer, 1961; Mitchell, 1966a,b). Mitchell (1966b) posed that the variability in diplopia thresholds measured by previous researchers may partly be due the use of stimuli in real space compared to stereoscopes, and changes in eye position. The experiments (2c and 3) support the position that eye movements caused greater variability in diplopia thresholds. I found little variability between observers in all experiments, as indicated by the standard errors of the mean; this was especially true when viewing time was limited to prevent vergence eye movements. Thus, I showed that even when testing naïve observers a short, but comfortable, viewing time leads to low variability in diplopia thresholds.

Future Directions

I hypothesized here that perceptual grouping would extend the fusion limit. In these experiments I presupposed that when the dots were connected they were perceived a single object, however I did not verify this. Therefore, in a subsequent experiment we will investigate

the degree to which the element configurations are perceived as objects. To quantify the relationship between the manipulation (i.e., addition of horizontal lines between elements) and uniform connectedness, I will present stimuli from all experiments (shown in Figure 19) in 2D and ask observers to rate the degree to which the dot elements appear as a single object. Results from this experiment will allow me to verify that the connectedness manipulations did in fact group the dot elements into objects, and to correlate these ratings with diplopia thresholds for each configuration.

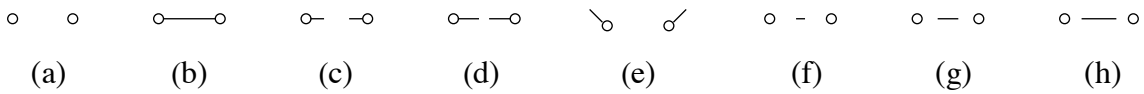

Figure 19. Stimuli for use in a connectedness rating experiment with all element configurations used in Experiments 1-5.

As discussed above, the experiments presented here do not allow me to distinguish between the grouping proposal and the low-level account based on receptive field size. In another experiment, I propose to do so by manipulating the perceptual grouping within the element configuration while not changing element size. I will vary element connectedness through element misalignment rather than line length. In this experiment, I will use a subset of the stimuli employed in Experiment 4: elements in the isolated, connected, and the nearly connected conditions. Figure 16 shows that thresholds are the same for the full and high connectedness conditions. If this result is due to perceptual grouping then it should be possible to disrupt the grouping by slightly offsetting the pair of elements, so the lines no longer intersect. I will control for possibility that larger elements stimulate larger receptive fields, thereby increasing diplopia thresholds, by decoupling the grouping manipulation from changing element size. The length of the lines "touching" the elements will remain the same across all configurations. This way, the size of the stimuli created by the line and the dots will remain unchanged (see Figure 20).

(a) (b) (c) (d) (e) (f)

Figure 20. Illustration of five conditions where I manipulate grouping by adding small (b), intermediate (c) and large (d) misalignments of element pairs. Here (f) and (e) show connected elements at horizontal and angled orientations, respectively. The size of the gap (or length of the line) between elements in (a)-(d) is the same as the nearly connected (smallest gap) condition used in Experiment 4 (Figure 15 (c)).

As mentioned above, the underlying assumption behind the size-disparity correlation and receptive field size involved in diplopia threshold changes is that the perception of diplopia is determined by the smallest rather than largest scale disparity tuned receptive fields. That is, that the component features in isolated elements will stimulate receptive fields of sizes corresponding to the small dots. If this is the case, then, using the isolated elements (Figure 15 (a)), I expect that diplopia will be signalled by neurons with smaller receptive fields than stimuli in Figure 15 (b). The increased size of the configuration created when the dots are fully connected by a horizontal line will lead to stimulation of disparity-tuned neurons with larger receptive fields than those detecting the isolated small dots. Thus, these units signalling fusion or diplopia with larger receptive fields will process, or tolerate, a larger disparity before diplopia is signalled.

In the proposed experiment, if the large scale receptive fields are responsible for encoding disparity and signally diplopia, the nearly connected (Figure 20 (a)), slightly misaligned (b), and fully connected (f) element conditions should yield the same diplopia thresholds. Similarly, if a large receptive tuned to the orientations in the rotated disconnected (d) and connected elements (e) were responsible for encoding disparity, then those conditions again should also yield the same diplopia thresholds. The grouping hypothesis predicts diplopia thresholds will be elevated using connected elements. Thus, the thresholds obtained using the connected (e) elements will be greater than those from the misaligned (d) elements. Using a similar logic, the grouping hypothesis predicts the elements with greater misalignment ((c) and (d)) will yield lower thresholds than those that appear more connected ((a), (b), and (f)).

Considerations

Due to a coding error the number of ascending and descending trials was randomly determined (and not balanced) in Experiments 3, 4 and 5 and the starting point for each trial was not recorded. Because of this, it is likely that there were unequal numbers of ascending vs. descending trials from session to session for each individual. While I was unable to determine the extent of the trial imbalance, the main result of this error should be an increase in inter-observer variability. To evaluate the effect of this error on variability in the results, I performed a bootstrap analysis of the variance obtained in the isolated and connected condition thresholds in all experiments (see Figure 21). The important comparison is between Experiment 2c which had balanced ascending and descending trials and Experiments 3, 4 and 5 which had similar experimental properties but potential bias. Results show that the confidence intervals for these conditions overlap, suggesting that the potential bias in Experiments 3, 4 and 5 did not substantially impact these data. Qualitative comparison of the variances across experiments shown in Figure 21 suggests that there was a much greater effect of exposure duration on variability than the potential testing asymmetry.

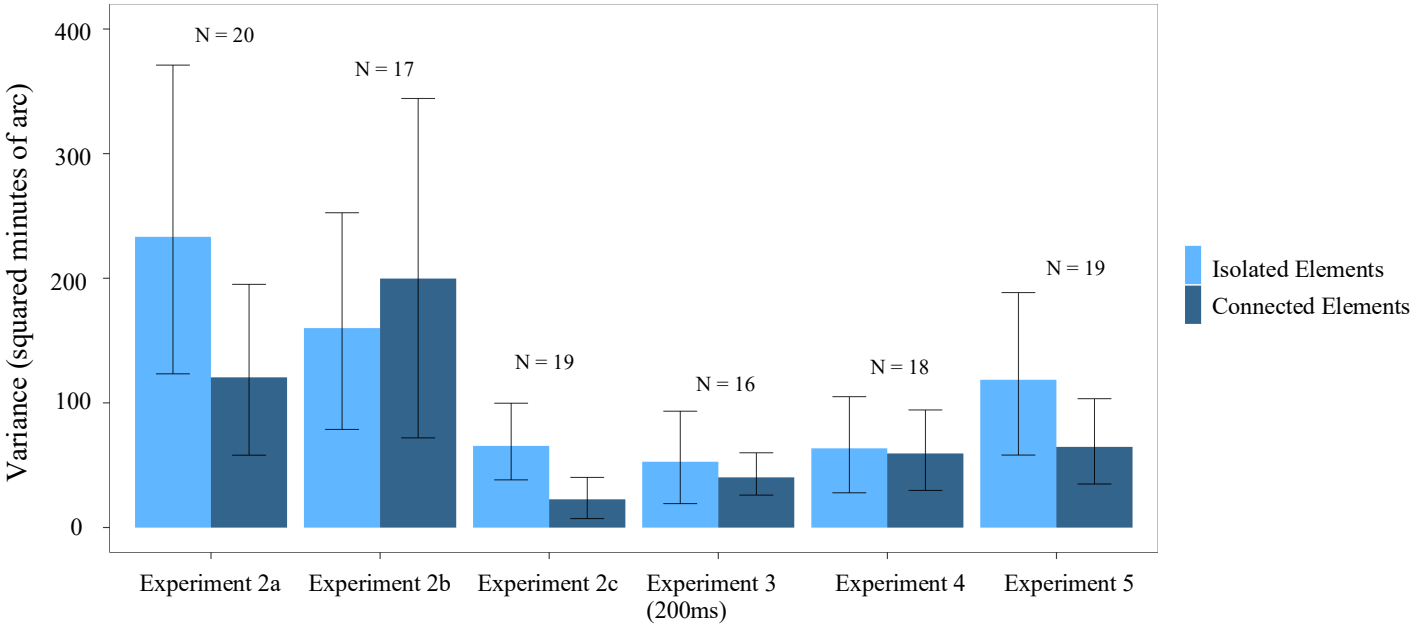

Figure 21. The variances associated with the diplopia thresholds obtained using isolated (light blue) and connected (dark blue) conditions in all experiments are shown here. Error bars show 95% confidence intervals obtained through a bootstrap statistical analysis in the variance found between observer thresholds.

Conclusion

Taken together, the results of the experiments reported here show that the diplopia threshold is consistently elevated when elements are connected to form an object. As discussed in the Introduction, it has been shown that low-level factors, such as retinal eccentricity, stimulus size, and element proximity influence fusion limits. The results suggest that perceptual organization also reduces the perception of diplopia. However, it is possible that that the size-disparity correlation may have also played a role here; additional experimentation is needed to determine the relative contribution of each.

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