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Effects of Processing Time and Stimulus Density on Apparent Width of the Oppel-Kundt Illusion

Sally Bailes

A Thesis
in
The Department
of Psychology

Presented in Partial Fulfilment of the Requirements
for the Degree of Doctor of Philosophy at
Concordia University
Montréal, Québec, Canada

January, 1995

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ISBN 0-612-05061-0

Abstract

Effects of Processing Time and Stimulus Density on Apparent Width of the Oppel-Kundt Illusion

Sally Bailes, Ph.D.
Concordia University, 1995

A conceptual model for size perception is proposed where perceived distance is a function of psychological velocity and processing time. Predictions from the model were tested in five experiments. Experiment 1 examined the effects of stimulus density and presentation velocity of filled and unfilled components of the Oppel-Kundt figure presented as though behind a moving window. Two levels of stimulus density were combined with two presentation velocities and each stimulus combination was compared with itself and every other. The results indicated that the combination of higher density and slower presentation velocity appeared widest and that the combination of lower density and faster presentation velocity appeared narrowest of all stimuli. Experiment 2 used magnitude estimates for stimulus combinations of three levels of stimulus density and three levels of presentation velocity. Faster velocity yielded smaller width estimates than slower velocity, as expected, but higher density yielded smaller width estimates than lower density, contrary to prediction. This apparent reversal of illusion effect was investigated in Experiment 3, where whole Oppel-Kundt figures were presented for very brief or prolonged durations. These results indicated that illusion strength increases with presentation duration and that, with a very brief presentation duration, the illusion can be eliminated or reversed. In Experiment 4, nine figures of densities were presented for prolonged durations in a paired comparison task. A non-linear, relative subjective width function was obtained indicating that apparent width increased with density until a maximum of 12 lines, after which subjective width decreased. Experiment 5 attempted to track the development of the Oppel-Kundt illusion for seven exposure times ranging up to 1 sec. for three figures of different stimulus density. The results indicated that illusion strength increased with time, that the density of the filled component of the stimulus affected illusion strength, and that significant reversal of illusion was found for the highest density stimulus at presentation durations of less than 200 ms. It was concluded that the data provided good support for the model; the terms of the model were further defined to include a role for spatial summation to predict reversal effects. The results were discussed in terms of magnocellular and parvocellular parallel processes.

Acknowledgements

The completion of any dissertation is a personal test of perseverance, resourcefulness, creativity, optimism, and self-confidence. However, the one single personal characteristic that decides the probability of success is the skill to have good people on your side. In this last respect alone, I never failed.

I am especially grateful to Charles White for accepting me as a graduate student at a time when I might easily have given up, and for remaining supervisor even after he moved to Florida. I thank him for his important contribution to all aspects of this thesis. When the research took an unexpected turn into the area of visual perception, I appreciated that I could approach him with the most basic questions and rely on his patience and good-humour.

I would like to remember the contribution of Bob Lambert who helped develop the theoretical ideas of the present thesis in the context of haptic perception.

I thank the members of my committee, Michael von Grünau and Mel Komoda, who contributed many interesting and practical ideas and who, together with the external examiners, Mike Mikaelian and Paul Albert, made my oral defence a very pleasant experience.

I had the good wishes and practical assistance of many friends and family members through the years. People variously helped with finding experimental subjects, being pilot subjects, editing drafts, and rehearsing for the oral

exam. In particular, Margaret Bailes, Rajesh Malik, Ken Evans, Madeleine Côté, Michael Bross, Helen Parent, Beverley Conrod and Mary Harsany all helped at some important stage.

Table of Contents

List of Figures and Table

List of Appendices

Introduction

The study of illusions is one of the oldest preoccupations of experimental psychology and many of the visual illusion phenomena we know of today were identified by early this century (Robinson, 1972). The word *illusion* comes from the Latin *illudere* which means "to make fun of". A closely related Latin word, *ludere*, "to play", gave rise to the English word, *elusive*. The irony of these etymological connections lies in the fact that although we have identified many of the characteristics of illusions, we still search for theories to explain them. Thus, after all this time, we remain somewhat eluded by them, if not actually made fun of.

Illusions have typically been treated as curiosities of visual perception, representing errors or mistakes more than anything else. The term "error" implies lawlessness and an apparent contradiction to the normal state of affairs. This conception is misleading because it ignores the fact that illusions are phenomena that are reasonably stable, consistent and apparently lawful. It is now increasingly recognised that illusion distortions are not just defective perceptions but possibly represent deviations from physical reality that are both meaningful and useful in our understanding of spatial perception in general, since they shed light on normal perceptual processes.

Taking this point of view, it becomes clear that illusions are not perceptual errors as much as perceptual compromises. The perceptual and sensory systems have an enormous range of complex tasks to perform, and the survival of the organism depends on these being carried out as swiftly and accurately as possible. On a constant basis, the perceptual systems must cut to the most essential information of all that is available from the external world. They must refine and process the information to make it intelligible to the organism. The organism cannot afford the time and energy it would require to arrive always at a percept that is in perfect correlation with the physical stimulus. Therefore, while the sensory and perceptual systems must be designed to give a quick, passable account of the stimulus, there will be a certain amount of stimulus information that is not processed with optimal accuracy. Certain types of these inaccuracies fall into the category of illusion. The ubiquitousness of the human species suggests that these perceptual compromises have not threatened survival on a large scale, though Coren and Girgus (1978) cite the case where the collision of two commercial aircraft could be traced to an optical illusion.

The main focus of this paper is on the perception of spatial extent and I shall review some theoretical attempts to explain illusions of size. Then I will review some literature that is pertinent to the question of how judgements of spatial extent are made, both in general and in the case of distortion of apparent size. To this end, I will make the case that two important characteristics of the perception of spatial extent that have not been fully integrated in theoretical accounts of size illusion are: processing time and stimulus density (or, spatial frequency). Since judgement of size is a task that is performed by both the visual and haptic senses, there will be emphasis on the communality between these two modalities. Finally, based on these ideas, I shall present a model for the perception of extent, and report five experiments to test the theoretical model.

Current Explanations of Size Illusions

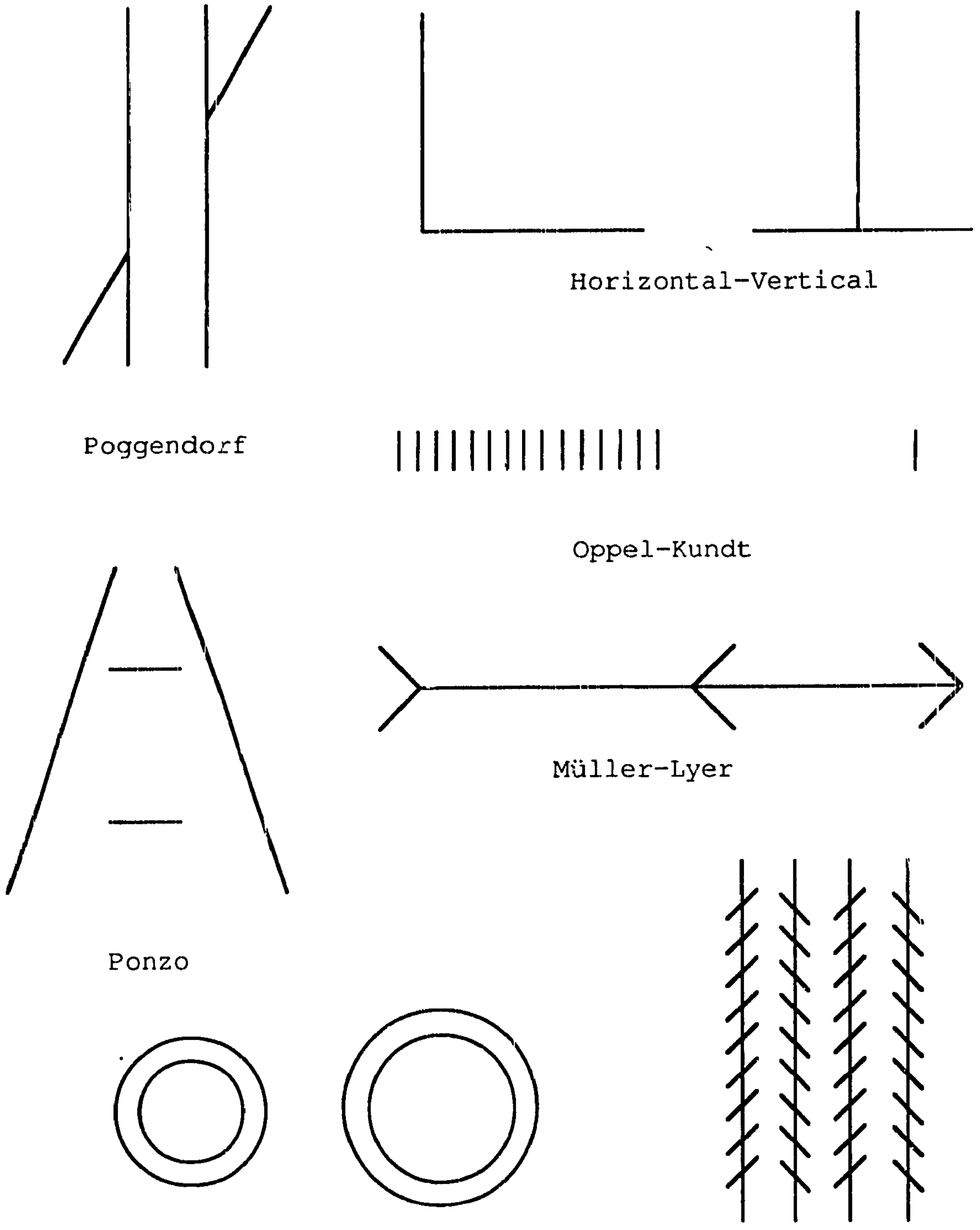
Coren and Girgus (1978) and Over (1968) have reviewed several explanations of visual illusions. Two main classes of theory emerge: the physiological, or structural; and the strategy explanations. According to Coren and Girgus, the structural explanations are those in which distortions result from properties of the eye or neural integration of the visual system at the level of the retina or beyond. Strategy explanations, which are more cognitive in nature, are those in which the distortions result from misapplied judgmental or attentional processes to specific attributes of the visual array. The difference between these two kinds of explanation may be equivalent to the difference between computer hardware and software functions or, in perception and neurophysiology, to the differences between bottom-up and top-down models of processing.

Structural explanations of illusions of extent tend to be rather less abundant than strategy explanations but more rooted in hard data. However, we do not yet fully understand the very intricate working of the neurophysiology of the visual system. Strategy explanations tend to be more elaborate and inclusive but less grounded in evidence that supports one explanation alone. It is important to note that some so-called strategy explanations invoke mechanisms that are pre-attentive in function so that their distinction from structural mechanisms is not very clear. Coren and Girgus (1978) pointed out that some strategy explanations may be more descriptive than explanatory. However, they do not specify that attentional and cognitive activities must also be bound to structure, but that these structures are too complex and too widely spread across the cortex to have been identified yet.

Therefore, strategy explanations may have wide currency until such time as a structural contribution becomes known. For example, if frogs were perception psychologists, or vice-versa, there would have been much learned discussion of reports that, when a small, dark spot moves across the visual field, the frog responds by flicking out its tongue in its direction. The phenomenon might have been called the "flying lunch" illusion, and a strategy explanation put forward that the frog was engaging in inappropriate insect constancy. This explanation might have held until such time as visual cells known as "bug detectors", particularly tuned to this stimulus configuration, were identified. In any event, the structural and strategy categories provide a useful way to organise these theoretical discussions.

Structural Mechanisms. According to Coren and Girgus (1978), structural mechanisms of illusion occur within the optical characteristics of the eye, within the retinal mechanisms such as lateral inhibition, and within the visual-cortical functions, which further refine and process the information. Each of these mechanisms contributes to the final illusion effect. There is some evidence that some portion of illusions of extent may begin with the structure of the eye causing chromatic and spherical aberrations of light (e.g. Coren & Porac, 1979). Illusions containing acute angles, such as the Müller-Lyer illusion (see Figure 1 for examples of illusions referred to in the text), where blurring has the effect of shifting the apparent locus of the vertex slightly toward the inside of the angle (Ward & Coren, 1976).

Coren and Girgus (1978) and Coren (1970) presented and tested a hypothesis that retinal neural mechanisms such as summation and inhibition have a role in the perception of extent. When two spatially separate points of light are sufficiently proximal, the neural activity generated may be added together, resulting in the perception of one point of greater intensity than either of the original points. The apparent location of the perceived point may be off-set, thus giving an illusion of position, if not extent. Both summation and inhibition may operate on intersecting lines so that the energy potentials of adjacent points are added with apparent shifts in position while points sufficiently distant



Poggendorf

Horizontal-Vertical

Oppel-Kundt

Müller-Lyer

Ponzo

Delboeuf

Zöllner

Figure 1.Geometric Illusions Mentioned in the Text

may exert inhibitory effects so that apparent distances may be slightly exaggerated. Brightness contrast has a role in either enhancing or reducing the magnitude of the illusion, since this affects the degree of the inhibitory mechanism. However, Butler (1981) challenged this hypothesis, since he failed to obtain changes in illusion strength due to brightness contrast, when the vanes-inward component was used.

While knowledge of the neurophysiology of the visual system and the arrangements of the different types of cells and their specialised functions continues to grow, it is generally understood that there are two primary mechanisms for processing visual information. Breitmeyer and Ganz (1976) reviewed literature on the difference between transient and sustained processes, and Livingstone and Hubel (1988) have discussed the structural and functional differences between the magnocellular and parvocellular systems. Transient processing tends to be associated with the magnocellular structures and is thought to be geared toward stimuli that are of lower spatial frequency, of brief duration or having rapid movement, and is sensitive to high contrast stimuli. Sustained processing, associated with the parvocellular structures of the retino-cortical pathways, is called into action for a visual array that is of longer duration (since the cells are much slower acting), slow-moving, with different colours and high spatial frequencies. The neural signals arriving at these structures prevail in the foveal region of the retina, which are densely organised and associated with high acuity daytime vision. The transient processes are essentially colour-blind and seem to involve retino-cortical pathways that originate from either the fovea or periphery of the retina.

It is not immediately clear how each of these different structural mechanisms play a role in illusions of extent. However, some researchers have suggested that many illusions are based on the lower spatial frequency components of the stimulus. For example, Carrasco, Figueroa and Willen (1986) found significant decrement of the Müller-Lyer illusion when there was prior adaptation to a vertical, low spatial frequency grating and no decrement with prior adaptation to a high spatial frequency grating or to a horizontal grating of any frequency.

Livingstone and Hubel (1988) reported that illusions involving perspective disappear when presented in equiluminant colours, suggesting that the mechanism for size illusions may be part of the magnocellular system. On the other hand, Pollack and Jaeger (1991) reported a strong Müller-Lyer effect when the figures were equiluminant colours. When the figures were coloured but with slight brightness contrast, they found a decrease in illusion strength. They concluded that the illusion does exist within the parvocellular system.

Zeki (1993) cautioned that equiluminance experiments may be premised on an over-zealous assumption about the degree of specialisation of the parvocellular and magnocellular systems. In fact, there is considerable interaction between the two systems, or at least, duplication of function.

Strategy Mechanisms. These explanations of illusions of extent are based on constancy strategies, on perceptual averaging strategies, as given by the eye movement readiness and assimilation theories, and on attentional strategies, as given by Piaget's (1969) centration theory.

Gregory's size constancy scaling explanation relies on the tendency of the visual system to interpret depth information from the stimulus array (Gregory, 1963; 1972). Since the perception of depth is a construction from information extracted from two flat planes, it is thought that some illusion figures contain elements that are inappropriately treated as depth cues. In the examples of the Müller-Lyer and Ponzo illusions, converging lines are treated as indications of perspective. The apparent dimensions of same-size targets are scaled according to their nearness to the vanishing point of an array, on the assumption that the more distant target ought to appear smaller than the nearer. If the two are equal, then the apparently more distant target is construed as larger than the apparently nearer.

The following two explanations each involve a kind of averaging of stimulus information, producing apparent distortion of length. According to Pressey (1971; 1972), assimilation theory states that, contained within the area of an optical illusion figure and parallel to the test extent, are a number of hypothetical contextual magnitudes that may be longer or shorter than the test extent. The test extent then apparently elongates or shrinks in proportion to the size and number of the contextual magnitudes. In addition, the contribution of any one contextual magnitude on illusion distortion depends on its distance from the centre of the field of attention. Pressey (1971; 1972) has worked out an equation in which illusion magnitude is said to be the sum of the differences between the physical and the hypothetical contextual magnitudes, taking into account the proximity of the contextual magnitude to the attentive field.

The second averaging type explanation, the eye movement/efferent readiness theory, supposes that eye movements determine distortions of perceived extent, but shares some common elements with Pressey's explanation. Measurement of eye movements while observers view illusion figures has led to the observation that eye movement patterns and judgement errors are correlated. Festinger, White and Allyn (1968) reported that the magnitude of the illusion effect for individual observers could be predicted by the extent of their eye movements.

According to Coren (1986), scanning paths will be influenced by certain features of the stimulus. An observer will tend to fixate a target so that it falls in the centre of the fovea. If there is an extraneous stimulus within a certain region surrounding the target, this is included in the foveal region with the result that the fixation point may be some average distance between the target and extraneous points, called the "centre of gravity". Thus, when the observer scans between two targets, the length of the eye movement will be affected by any other information in the near vicinity. An explanation of the Müller-Lyer illusion, for example, is that for the portion with out-going vanes, eye movements would be drawn beyond the vertices, whereas for the portion with in-going vanes, eye movements would undershoot the distance between the vertices, causing over- and under-estimation of extent, respectively. If the extraneous stimulus is too far away from the target, then it fails to exert any influence on eye movements.

Limitations of the eye movement explanation, as noted by Over (1968) and Robinson (1972), arise from reports that several illusions that seem to persist even though the image is stabilised on the retina, either with a special contact lens mounted directly onto the cornea or using flash-induced afterimages. Apparently, the perception of illusion is not strictly dependent on eye movements. However, Festinger et al. (1968) and more recently Coren (1986) have proposed that the eye movements themselves need not be executed but that it is enough that the intended eye movements are calculated and reserved as "efferent readinesses".

Coren (1986) admits that one of the main criticisms of the theory is that it is difficult to demonstrate the direction of causality in this situation: Do errant eye movements cause distortion or, are they the result of it? This problem is made more difficult by the efferent readiness proposition: a readiness, though a handy explanatory mechanism, is exceedingly difficult to pin down experimentally, unlike actual eye movements. For the efferent proposition to work it is necessary to presuppose that there is some rudimentary pattern recognition possible within very brief intervals from which these readinesses may be calculated.

Piaget's (1969) law of relative centrations can be summarised briefly as follows: elements of a figure that are fixated tend to be over-estimated in size and these distortions can be corrected through "decentration". Centrations are acts of attention or fixation that vary in order, duration and intensity and which are influenced by the retinal area stimulated and by visual acuity. The features of the stimulus seem to determine the patterns of fixation and attention: detailed parts of a stimulus attract more centrations and are therefore perceived as larger. When two contours of unequal size are adjacent, the larger attracts more centrations than the smaller, with the result that the larger is overestimated in extent. These distortions can be somewhat corrected with repeated experience of the array. The theory does attempt to incorporate both scanning patterns and attention processes in a theoretically useful way.

Given the similarity between Piaget's centrations which are attentional in nature and Pressey's use of contextual magnitudes within a field of attention, it is apparent that these theories appeal essentially to the same underlying strategies of the visual system.

Coren and Ward (1979) pointed out that there has not been a single explanation that can account for all optical illusions or even necessarily all of the observed effects of any one illusion. This is not surprising since the processing of information occurs at several levels of the visual system. Different structural and strategy mechanisms may be invoked by different illusion stimuli. These may be processed serially and in an additive way from eye to cortex; or, the contributions from different mechanisms may be processed in parallel, in which case the final percept may represent some average of these. Finally, when we maintain the view that the visual system is designed to accomplish a variety of tasks and that illusions are the result of compromise solutions to the number and complexity of these tasks, then it is only reasonable to assume that there is not one unified theory to account for all observed illusions.

If illusions of extent are the product of the visual system's general rules of resolving spatial information, then what happens in the perception of spatial extent in the general case? The following studies shed light on how spatial extent is processed, whether or not the final percept represents an illusion distortion. The following two sections examine some findings relating apparent size and time in vision and in haptic perception.

Phenomenal Space and Time

The *tau* and *kappa* effects suggest that space and time are subjectively inseparable quantities in both the visual and haptic perception of extent. The *tau* effect occurs when the subjective estimation of an otherwise constant spatial extent varies as a function of the temporal separation between one end of the spatial extent and the other. Bill and Teft (1969) varied intervals between two flashing lights which were spatially displaced and had observers adjust the position of a third light according to the apparent distance between the flashing points. As inter-flash intervals increased, apparent distances decreased. They did not report any information about eye movement. The *kappa* effect occurs when a constant time interval varies in subjective duration when it is demarcated by stimulus points spanning physical extents of different sizes (Cohen, Hansel & Sylvester, 1953; Price-Williams, 1954).

Another line of evidence for the role of temporal information in the judgement of spatial extent in visual perception comes from the anorthoscopic effect, first described by Zöllner and Helmholtz in the late 1800s (Robinson, 1972) and more recently from Anstis and Atkinson (1967) and Morgan (1981). The anorthoscopic effect involves moving a line drawing stimulus to and fro behind a stationary narrow slit. Observers are able to perceive the entire drawing. Anstis and Atkinson (1967) demonstrated that the apparent shape of a stimulus is dependent on the subject's speed of eye movement. They presented an ellipse or circle oscillating behind a stationary vertical slit and controlled the subject's rate of eye movements by having them track a spot of light which oscillated in phase with the stimulus but with various amplitudes. The observers' task was to adjust the shape of the perceived stimulus so that it appeared circular. They found that with increasing rate of eye movement, the greater the vertical adjustment necessary to maintain the circular appearance of the stimulus figure. Furthermore, when eye movements moved in the opposite direction to stimulus oscillations, the stimulus appeared to be both reversed in orientation and compressed in size. They concluded that the subject's percept was based entirely on the retinal image, that the speed of eye movements determined how the image was to be "painted" on the retina. They also noted that eye movements are seemingly necessary for shape perception as no shape was reported before the occurrence of tracking eye movement.

Day and Duffy (1988) examined the effect of movement velocity on the perceived extent of the Müller-Lyer illusion using the anorthoscopic paradigm in vision. First, they observed that the Müller-Lyer illusion was present when the figure was viewed moving behind a narrow slit in its whole form, though the strength of the illusion was about half that when the figure was presented whole, whether moving or stationary. In addition, it was apparent that the observers perceived the component with out-going vanes as taking longer to pass the slit than the figure with in-going vanes, where the inter-apical extent and time to pass the slit were in fact equal. When the two components of the figure were presented successively and the velocity of the stimulus movement varied, some interesting results were obtained: first, the condition in which the component with out-going vanes was presented slowly and the component with in-going vanes was presented relatively fast, the magnitude of the illusion was much greater than the equal-velocity control; second, the condition in which the out-going component was presented quickly and the in-going component comparatively slowly, the magnitude of the illusion was greatly reduced from the control condition. The authors concluded that the amount of time taken to pass the slit served as the reference for spatial extent. One problem with this design could be that the stimulus is apparently featureless between the vanes (except for a straight line) so that there would be no possible reference for extent except for the time between the appearances of the vanes. In other words, it would seem difficult to tell how fast a straight, horizontal line moves in a horizontal direction past a narrow slit, or tell in fact, whether there was any movement at all.

Day and Duffy's experiment can be explained in terms of some of the ideas discussed above. First of all, passing the two components behind the slit when the duration of the presentation of each component was equal resulted in illusion magnitude of about half the usual strength. This portion of the illusion magnitude can be accounted for by Coren's centre of gravity hypothesis. The position of the vanes causes the visual system to over- and under-estimate the distance between the vertices. However, the estimated time it takes for the figure to pass the slit can increase the illusion magnitude. It increases by a lot or a little, depending on the speed of the movement. In the typical way of viewing the Müller-Lyer figure, that is, stationary and in full view, the visual system estimates the distance between the two pairs of vertices taking into account the distance traversed which is influenced by the position of the vanes. Therefore, the system estimates the distance between the two centres of gravity, rather than the vertices. This distance is then further modified by the estimate of the time taken to scan between the two centres of gravity.

Evidence from Haptic Perception

Most illusion research has focused on distortions occurring in visual perception, even though it has been amply demonstrated that illusion phenomena exist in the auditory and haptic perceptual systems. It has been known for more than 50 years that not only do illusions occur in the haptic or touch modality but that many of the same illusions exist analogously in haptics and vision (Revesz, 1934). Even in the context of the overwhelming predominance of visual research in perception, it is nevertheless surprising that haptic illusions have been generally ignored in recent discussions of theories of illusions. Robinson (1972), in his otherwise very comprehensive review, gave them only very brief mention and Coren (Coren & Girgus, 1978; Coren, 1986) did not take them into account in his version of the eye movement/efferent readiness theory. Only Over (1968) has attempted in a major review of illusion theories to suggest that haptic phenomena have any explanatory value in our general understanding of illusions.

Revesz (1934, 1953) reported as many as 29 geometric illusions when blindfolded sighted observers were permitted exploratory use of their hands (active touch) and many were found when the stimuli were pressed repeatedly onto the palm of the subject's hand (passive touch). These included illusions (and their variations) of extent, such as the horizontal-vertical, Müller-Lyer, filled-unfilled extent, and Delboeuf illusions, as well as illusions of direction and angle, such as the Poggendorf and Zöllner illusion (see Figure 1).

Several authors (Revesz, 1934; Hatwell, 1960; Tsai, 1967; Patterson & Deffenbacher, 1972; Pasnak & Ahr, 1970) have investigated blind observers' responses to classical geometric illusions and their findings support the idea that geometric illusions are not exclusively visual in nature. Revesz (1934) found positive effects to several illusions of extent, including the horizontal-vertical illusion, and illusions of angle while Pasnak and Ahr (1970) found that the Poggendorf illusion worked for the blind. It has been widely reported that the blind give a similar response to the

Müller-Lyer illusion as do the sighted (e.g., Hatwell, 1960; Patterson and Deffenbacher, 1972; Tsai, 1967). These studies suffer somewhat from small sample sizes and it is not always clear that the experimenters have differentiated between the congenitally and adventitiously blind. This is an important distinction if it is to be demonstrated that the illusion effects are independent of experiential variables related specifically to vision.

However, the fact that the congenitally blind may respond in much the same way to raised relief illusion patterns as the sighted do to paper and ink patterns makes the haptic sense an appropriate test case for theories of geometric illusion. Insofar as they address analogous illusions, explanations that can encompass data from both sense modalities should have more credibility than those that are constrained to visual perception. For example, the size constancy explanation of the Müller-Lyer illusion would have to include an account of why blind observers should interpret depth cues in the same way as sighted observers.

Some studies, testing an analogous "eye movement" theory for haptics, have found that scanning movements are in some ways correlated with apparent extent. It has been observed that the slower a scanning movement across an extent, the longer its apparent length, demonstrating the *tau* effect for haptic perception. Helson and King (1931) administered two points of stimulation successively on the skin surface and varied the interval between the two points, holding the actual spatial displacement of the two points constant on the skin. With smaller time intervals between the two points, apparent distance between the points seemed to decrease and larger intervals produced greater extent estimates. Wapner, Weinberg, Glick and Rand (1967) found that as a subject's limb was moved at different rates over a stimulus, slower movements corresponded with larger distance estimates.

Coren's centre of gravity hypothesis is not supported in haptic perception, insofar as Wong (1975) and Over (1966) concluded that illusion effects could not be altered by extending haptic exploration beyond the limits of the stimulus. For example, Wong's observers were required to inspect raised-edge Müller-Lyer stimuli in which the main shaft was extended beyond the juncture of the in- and out-going vanes along the full length of the shafts. One group inspected the extended Müller-Lyer figures while another group received unmodified Müller-Lyer figures. The typical illusion effect was evident in both conditions but the extent of excursive limb movements had little effect on illusion magnitude.

The following studies have tried to determine what is important about haptic scanning movements in the perception of spatial extent. These have mainly focused on the horizontal-vertical illusion in which, in visual perception, a vertical line is typically seen as longer than a horizontal line of equal length. There have been numerous reports that the haptic illusion exists with both L and inverted-T figures for blind and blindfolded sighted observers (e.g., Revesz, 1934; Reid 1954; Bean, 1938; Hatwell, 1960; Tedford & Tudor, 1960).

A number of studies have identified the type of excursive movement as an important determinant of the haptic horizontal-vertical illusion. Day and Wong (1971), Reid (1954) and Davidson and Cheng (1964) found that exploratory movements which are radial relative to the subject tend to result in over-estimation of extent compared to movements which are tangential. This effect is quite stable even when the orientation of the figures was changed from the horizontal/radial to the fronto-parallel plane relative to the subject, or when the figures were rotated relative to the subject.

This relationship between type of movement, radial or tangential, and strength of the illusion of extent appeared to be consistent through a number of orientations to the extent that Deregowski and Ellis (1972) devised a mathematical prediction that worked reasonably well to predict illusion in other experiments (e.g., von Collani 1979, Day and Wong, 1971). Their formula took into account the orientation of the stimulus relative to the subject and the proportion of radial-to-tangential movements, illusion effects being strongest where purely radial and tangential movements are present and absent at the point where the ratio of radial to tangential was equal for both arms of the figure.

Wong (1977, 1979) observed that radial movements tended to be carried out more slowly than tangential movements of the same length. The time of movement execution to scan a fixed length at different angles of rotation in the horizontal plane tended to be related to the ratio of radial-to-tangential movement. The greater the radial component was, the slower the speed of execution of the limb movement and the larger the over-estimation of extent. In another experiment, Wong (1977) found that observers were able to assess time differences between the two types of movement. He concluded that haptic extents are judged on the basis of movement duration rather than velocity. Moreover, in a developmental study, Wong (1979) found that children who took more time to inspect the stimulus figures (L-figure) showed greater illusion strength.

Wong (1977) proposed slower radial movements might be due to the greater mechanical resistance produced by the limbs and joints for that type of movement. Therefore, Marchetti and Lederman (1983) attempted to change the inertial properties of a scanning task by presenting the stimulus some distance away from the subject's body and by adding weight on the subject's hand. In both cases, alterations in inertia did not support Wong's hypothesis. Unfortunately, they did not take into account how their inertia changes affected the observers' scanning duration.

This set of studies demonstrates some important points about how size is determined in haptic perception. First, the studies by Wong (1975) and Over (1966) demonstrated that in haptics, the extent of the excursive movements alone is not sufficient to account for illusion effects. Next, it was demonstrated that type of haptic movement (radial or tangential) has a great deal to do with the over- and underestimation of extent. Furthermore, and of direct importance to the present thesis, one critical difference between radial and tangential movements is the duration of the movements and this temporal constituent affects the perception of extent.

This evidence from vision and haptics demonstrates the need to take both spatial and temporal factors into account in the perception of spatial extent. The next section reviews evidence that the spatial frequency of the stimulus plays a role in the perception of spatial extent.

Size, Spatial Frequency and Subjective Time

A few studies have suggested the importance of the interrelation among spatial scale, spatial frequency and the subjective experience of time. DeLong (1981) had adult observers carry out activities in scaled-down, furnished rooms (three sizes) by manipulating appropriately sized dolls, imagining that they were themselves performing the activities. The observers were asked to indicate when they felt 30 minutes had elapsed. Observers' time estimates bore a proportionate reduction with the scale of the model room, while time estimates made in a normally scaled room (no doll) were close to real time. For example, 30 minutes were judged to have elapsed in about four minutes in a model room of scale 1/6. It is unclear how the observers construed the task: for example, did they really believe that four minutes seemed like thirty? Nevertheless, DeLong concluded that judgements of space and time are made relative to one another. Hughes, Lishman and Parker (1992) made 40 ms. presentations of a picture of an outdoors scene where the picture contained the wide spatial frequency band-width or where the spatial frequency of the images had been altered using high- and low-pass bandwidth filters. In a paired-comparison task, observers selected the picture for which the duration seemed longer. They found that the picture with the wide range of spatial frequencies was seen as apparently longer in duration than any of the altered pictures. The authors rejected the possible involvement of visual persistence and concluded that spatial information must be coded and then neurally integrated. Thus, spatially complex patterns may be phenomenally longer in duration because this task of integration takes longer.

The filled duration illusion (Buffardi, 1971) is one that occurs in vision, haptics and audition. Essentially, an interval of time during which discrete stimulus events occur is perceived as longer than the same interval without intervening stimulation. Buffardi's study showed remarkable correspondence among the three modalities. The perception of duration was affected by the number of intervening elements as well as their arrangement within the interval. Time intervals with evenly placed elements were judged as longer in duration than the same intervals containing elements in an asymmetrical pattern. However, the effects of stimulus configurations seemed to be secondary compared to the number of elements. Buffardi concluded that the perception of duration was related to the amount of information occurring in the duration and attributed this to the cognitive process of counting.

Russo and Dellantonio (1989) examined the role of phenomenal (or, subjective) time on the estimation of spatial extent. This work attempts to show the connection between perceptual space-time and the stimulus density variable. Their experimental task consisted of the application of three tactile stimuli in a straight line spatially separated along the length of the arm. At the same time that the tactile stimuli were applied, an audible tone was sounded. The subject was asked to judge whether the second interval (spatial or temporal, depending on the task requirements) was greater, smaller or equal to the first interval. The first experiment was simply a verification of the illusion for temporal intervals, whereby a filled time interval is subjectively longer than an unfilled interval of the same duration. In any given trial, the observers received three auditory/tactile stimuli separated by equal time intervals and equal topographical distances. Within one of the two intervals, two to four intermediate auditory signals were presented. Temporal intervals containing auditory signals were judged as longer in duration than blank intervals. In another experiment, Russo and Dellantonio examined the effect of duration of the interval on the estimated spatial extent defined by the interval. Given two physically equal extents, the one defined by a longer temporal interval was judged as longer in spatial extent, supporting previous observations on the *tau* effect.

It is, however, their final experiment that is most interesting in that they used the effect of the filled versus unfilled temporal interval to produce a phenomenal distortion in duration as the temporal manipulation for the *tau* effect. In other words, they repeated the second experiment but used the filled- unfilled interval distortion instead of manipulating physical time in order to produce the *tau* effect. In this instance, intervals characterised by equal spatial extent and equal physical duration were judged as longer when they contained auditory stimuli compared to blank intervals.

Spatial Extent as a Function of Time and Density

Many studies were reviewed above that indicate that the encoding of spatial extent is related to temporal factors. Temporal estimations are determined by summation processes at several levels of neural processing. Subjective time estimates are longer when viewing more detailed patterns than when viewing less detailed patterns. Processing time, whether spent in scanning early in the visual process or in neural processing at higher levels, in part determines perceived spatial extent. If we consider the most simple and observable situation, when an eye movement or hand scan occurs between two points, perceived distance is influenced by the time it takes to execute the movement: if it is executed more slowly, the perceived distance is correspondingly longer and vice versa. If the length of the scanning movement is altered by virtue of stimulus features, such as outward- or inward-going vanes, it is the difference in time of execution that mediates the difference in perceived extent.

Buffardi's study demonstrates that event-filled temporal intervals are judged as longer in the haptic, visual and auditory modalities. We can assume, then, that processing time, spent in scanning movements and/or higher processing, that is punctuated with discrete stimulus elements will influence the perception of extent because it is in part a problem of filled duration. One can see the relationship with Piaget's centration hypothesis, though it is not necessary to suppose that the processing of density information involves attentional activity.

Summarising these points, the perception of spatial extent can be considered a function of three components: 1) the physical extent itself, the initial percept of which is modified by 2) the amount of processing time, whether there is active scanning or not, and also modified by 3) the density of the stimulus, that is, the number of perceptible events contained within the extent.

Since the evidence shows very consistently that time is involved in the perception of spatial extent, it is likely that temporal summation may produce a trade-off relationship between stimulus density and time, in a similar way that reciprocal energy relationships have been described between intensity and time (Bloch's Law) and intensity and area (Ricco's Law and Piper's Law). The simplest case for perceived extent is evident from the *tau* effect where there is a constant physical distance between two successively flashing lights and no stimulus elements occurring within the interval. The perceived distance between the lights is directly related to the inter-flash time, as shown by the function n = 0 in Figure 2, n being the number of density elements in the array. Figure 2 shows similar functions for cases where there are intervening density elements. The density/time trade-off is evident when a horizontal line is drawn across these density functions showing how density and time change to keep perceived extent constant. Note that these functions are described by the equation for a simple linear function describing the relationship of two variables, where a is the slope and b is the y-intercept:

$$y = ax + b. \tag{1}$$

This equation provides the general format for a model that predicts perceived extent as a function of time and density, to be stated in psychophysical terms. In other situations, real distances (d) are determined from the product of the average velocity (v) of motion and the elapsed time (t), given in this familiar equation:

$$d = v\ t, \tag{2}$$

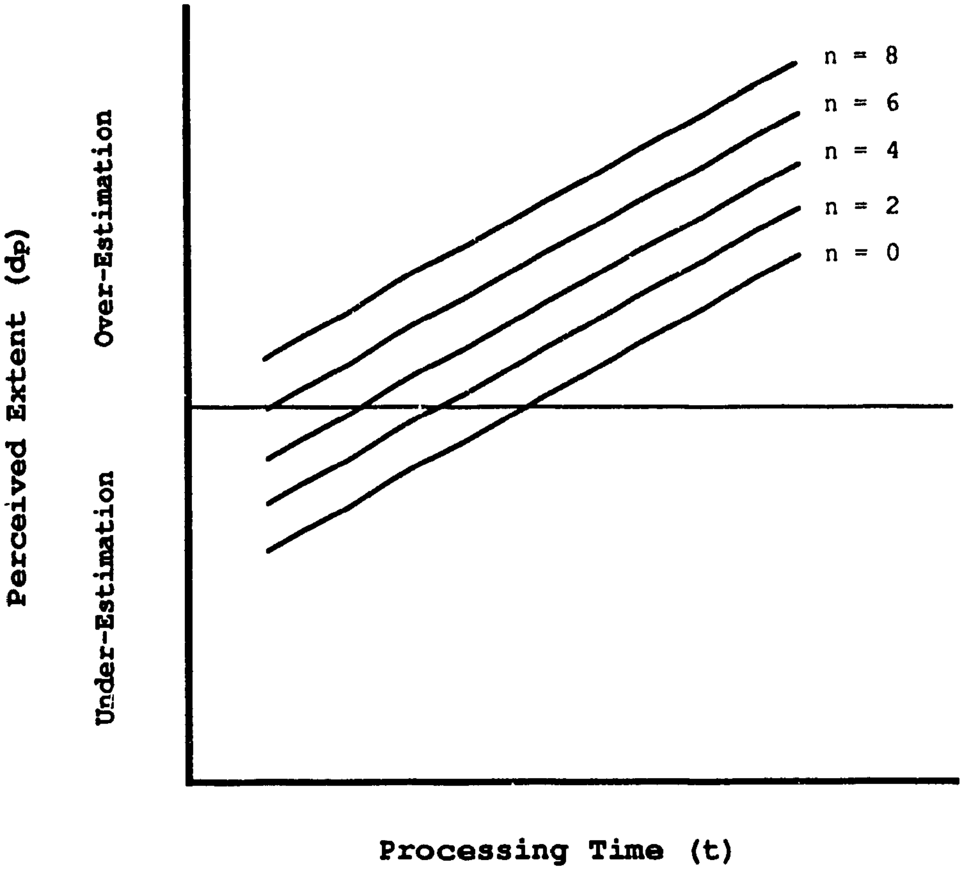


Figure 2. Schematic Model For Perceived Extent As A Function Of Time And Density

Equations 1 and 2 provide the basis for a purely heuristic conceptual model for the perceptual estimation of spatial extent that is presented in the following equation:

$$d_p = v_\psi (t_0 + \sum_{n=1}^{m} t_n) + k, \tag{3}$$

Where:
d_p is the perceived distance between two points,
v_ψ is a perceptual analogue to velocity,
n is the number of density elements processed,
m is the maximum number of density elements contained in the stimulus array,
t_0 is processing time when there are no density elements, i.e., when $m = 0$,
t_n is processing time for any density element, and
k is the perceived extent based on the area of retinotopic activation.

In this model, time is intended very generally to mean processing time regardless of what stage is involved, peripheral or cortical. In most cases, where there is active scanning either by eye movements or by haptic exploration, scanning movements will account for some portion of processing time. However, the model should also account for conditions in which there are no scanning movements per se. This can be done by assuming the existence of a basic temporal processing unit such that each unit of psychological time is associated with a unit of spatial distance. We can refer to a basic ratio of distance to time as psychological velocity, or v_ψ .

Next, the time component of the model is elaborated in terms of the density of the stimulus, in order to account for the situation in which an otherwise uniform extent containing stimulus elements appears to be larger than one containing fewer elements. The terms in the brackets take into account the summation properties of the perceptual system. The term, t_0, represents the time to process the empty interval and the summation term accounts for the time required to process the n stimulus elements. The term k is a constant minimum perceived extent, based on the physical dimensions of the extent, based on the scaled retinotopic layout of stimulation.

Note that this model, while presented in mathematical terms, is not expected at this stage to yield precise values for d_p since values for v_ψ and the precise amount of processing time devoted to each density element cannot be determined at present. However, if it is taken as a general model, some predictions can still be tested: 1) Varying the time and density of a stimulus should yield a set of linear functions similar to those presented in Figure 2. Increases in both stimulus density and overall processing time will effect greater perceived extent and these effects are additive; 2) These functions should hold whether or not there is eye movement or haptic scanning, or regardless of the degree to which these are limited or controlled. This is because active scanning is a subtype of temporal processing of which primarily the total processing time is important; and 3) Under-estimation of the physical extent can occur with briefer processing time and/or with lower stimulus density, as shown in Figure 2.

In the series of experiments to follow, the time and density parameters contained in the model expressed in Equation 3 were observed in the context of the filled and unfilled extent illusion. This illusion, in which a filled extent appears wider than an unfilled extent of the same physical width, is most commonly known in its Oppel-Kundt variant. Stimulus density is operationally determined by the number of vertical line elements contained within the extent, demarcated by the outermost lines of the extent. Temporal parameters were manipulated both by sequential presentation of the stimulus elements at varying rates (velocities) in two experiments and by stimulus onset duration of the whole stimulus in the remaining experiments.

Experiment 1

The purpose of this experiment was to establish whether density and temporal effects could be obtained through the visual presentation of stimuli on a computer screen, using successive presentation of each component of the filled-unfilled space illusion. The stimuli were presented as though behind a window moving from left to right. On the basis of the model shown in Figure 2, it was predicted that 1) a higher density stimulus would be judged as appearing wider than a lower density stimulus of equal physical width and that 2) a stimulus presented more slowly from beginning to end would be judged wider than the same stimulus presented more quickly.

The four combinations of these parameters and their predicted effects were as follows: (1) The stimulus combining high density with slow presentation would be most frequently rated as appearing wider than any other stimulus combination; (2) The stimulus combination combining low density and fast presentation would be least often rated as appearing wider than other combinations; (3) The combinations of high density with fast presentation and of low density with slow presentation would have some effect intermediate to effects (1) and (2) above, and possibly, closer to chance levels. Another aim of the study was to determine to what extent the observers' responses to the density/velocity combinations appeared to reflect an additive combination of their responses in the conditions in which only density or velocity were varied.

Method

Observers

The observers were seven volunteers, three males and four females, ranging in age from 19 to 58 years. The observers reported normal or corrected-to-normal visual acuity.

Design

The format of this study consisted of a paired comparison task using two stimulus configurations, high and low density, at two presentation rates, fast and slow. Each stimulus combination, i.e. low density/slow velocity, high density/slow velocity, low density/fast velocity, high density/fast velocity, was compared with every combination. Therefore, there were 16 different pairs of stimuli, taking into account the order of presentation, first or second. A summary of these comparisons is included in Appendix 1. These were presented in ten blocks of trials, each pair appearing once per block in random order, giving, in total, 160 trials.

Equipment and Materials

The equipment consisted of a Macintosh IIcx computer, Macintosh 13" high resolution colour monitor, HyperCard 2.0 software and MacroMind Director 1.0 software. The stimuli were generated using the MacroMind Director, and presentation rates and sequences were controlled using HyperCard software.

The stimuli consisted of identical vertical lines arranged in either a low density (two lines) or a high density (ten lines) configuration (see Figure 3). In both stimulus arrangements, the outermost lines spanned a width of 7.5 cm and the line height was 1.2 cm. The observers were seated at a viewing distance of approximately 100 to 150 cm from the computer screen, which they maintained throughout the testing session. Therefore, the visual angle subtended by the illuminated area of the screen was between 11.1 and 16.4 degrees and, by the stimuli, when entirely visible, ranged between 4.3 x 0.69 degrees and 2.9 x 0.45 degrees. Two presentation rates were used; the lines were presented sequentially from left to right, over intervals of 2.5 seconds (fast) or 4.5 seconds (slow). Luminance values for the screen and stimuli are given in Appendix 7.

Procedure

The observers were given a basic orientation to the use of the computer's mouse, as well as a trial run of the experimental task.

On each trial, observers saw two stimuli presented in succession. The first stimulus was presented three times and, following a brief pause, the second stimulus was presented three times. Then, the observers were asked to indicate which stimulus appeared to be wider between the two outermost lines. It was stressed to the observers that they should base their judgements on how the stimuli *appeared* to them and not to be overly concerned with working out what is

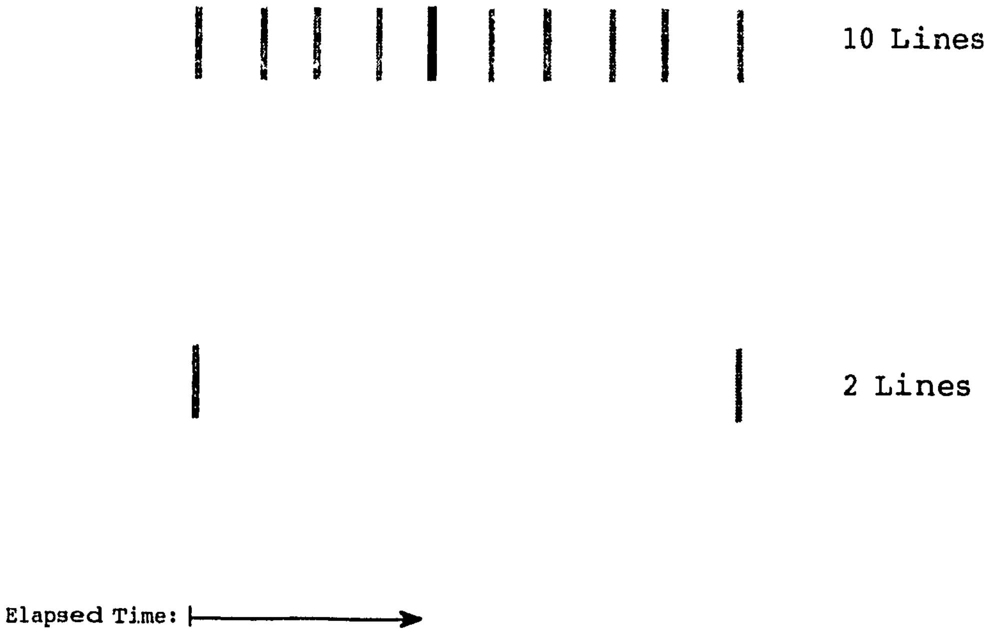


Figure 3. High (10 Lines) and Low (2 Lines) density stimuli presented sequentially. Shading indicates that only one element is visible at a time.

the actual state of affairs. Their choices were made by selecting one of two buttons marked "First" or "Second" using the computer's mouse. Trial presentation was controlled automatically by the computer, with rest pauses at the end of each block of 16 trials. Observers were encouraged to pause for a few minutes when they felt fatigued, in particular, at the half-way point. The entire experiment was generally completed in about 90 minutes.

Results

The data yielded by the experimental conditions can be considered as 1) simple velocity effects, where two stimuli of the same density were compared at different velocities; 2) simple density effects, where two stimuli were compared having the same velocity but differing in density; and 3) velocity x density effects, where two stimuli were compared that differed on both attributes. The responses were tabulated as frequencies of judgements rated in the predicted direction, that is, the frequency with which observers selected slow velocity as appearing wider than fast and high density as appearing wider than low density. The data are presented as proportions in tables in Appendix 2.

The mean proportion of wider judgements across observers for which, 1) fast and slow velocities were compared where the density was constant, and for which, 2) high and low densities were compared where the velocity was constant, are presented in Figure 4. For the density comparison, the *z*-score test for proportions, including continuity correction,

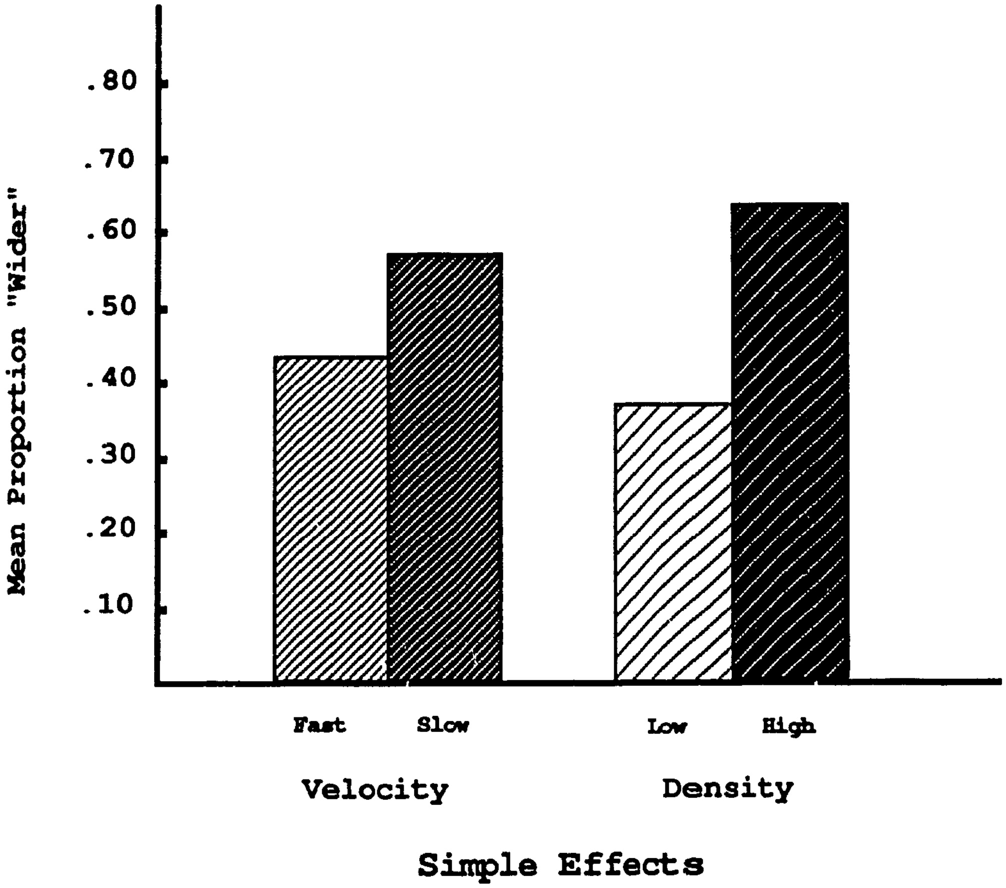


Figure 4. Mean Proportion "Wider" Judgements Comparing Fast Vs Slow Velocity When Density Is Constant And Comparing Low And High Density When Velocity Is Held Constant

was used to compare the proportion of "high density = wider" responses, 0.63 against the chance proportion of 0.5. The effect of density did not reach significance, $z = 1.43$, $p > .05$. Similarly, the observed proportions for fast and slow velocity appearing wider, given same density, did not differ from the chance proportion (0.5), $z = 0.76$, $p > .05$. Therefore, although these means tend to differ in the predicted direction, these differences are not statistically significant.

For further analysis, the high density/slow velocity stimulus was compared with the low density/fast velocity while the high density/fast velocity was compared with the low density/slow velocity. This latter condition is the one in which it was predicted that velocity and density effects might cancel one another. Mean proportions of wider judgements across observers for these conditions are presented in Figure 5.

Overall, the proportions for the slow velocity/high density condition and the fast velocity/low density conditions differed significantly from the chance proportion, 0.5 ($z = 2.23$, $p < .05$). As predicted, the high density/slow velocity stimulus and the low density/fast velocity stimulus demonstrated intermediate effects, and these proportions did not differ significantly from chance, $z = 1.09$, $p > .05$. Density appeared to be the more salient attribute, since comparisons between the "wider" proportions for high and low density show a significant difference, $z = 2.5$, $p < .01$,

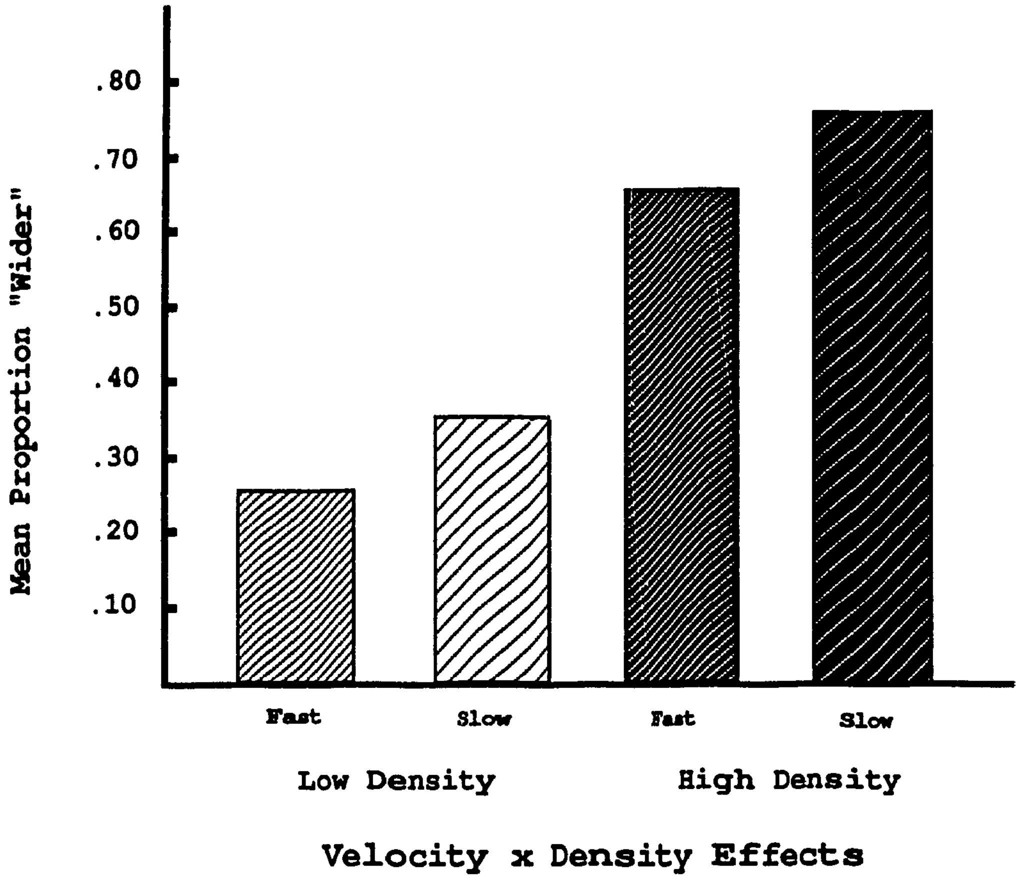


Figure 5. Mean Proportion "Wider" Judgements Comparing Four Combinations of Velocity and Density

while a similar comparison for slow and fast velocity was not significant, $z = 0.76$, $p > .05$.

Discussion

The results of this experiment support the predictions that the combination of slow presentation rate and high density would be judged as longer than the combination of fast presentation and low density. Also consistent with the prediction, the combinations of fast velocity/high density and slow velocity/low density yielded intermediate effects which did not differ from chance levels of responding.

Although the simple effects differed in the predicted direction, neither the velocity nor the density conditions alone resulted in significant changes in apparent width. It must therefore be concluded that the combined effects of velocity and density is additive. It appears that, given the stimulus parameters of the present experiment, the density effect is more salient than that of velocity. It should be noted that the presentation rates used in this experiment, while as rapid as the apparatus would allow, were exceedingly slow for visual perception. Therefore, faster presentation rates may enhance the salience of velocity as a simple effect.

In conclusion, this experiment demonstrated that the combination of the *tau* effect and filled-unfilled space illusion affects perceived extent, even though their separate effects were not significant within the parameters used here. This is consistent with the results of Russo and Dellantonio

(1989) in which the *tau* effect was combined with an auditory density stimulus to increase the perceived separation between two points on the surface of the skin. The approach used in the present experiment is more directly related to visual processing of spatial extent.

To determine the quantitative parameters of these stimulus attributes, the purpose of the next experiment, therefore, was to obtain magnitude estimates for these effects. An additional purpose was to employ faster presentation rates as well as to introduce more variation in the density condition, in order to enhance both velocity and density as simple effects.

Experiment 2

The purpose of this experiment was to measure the magnitude of the effects of time/velocity and density on observers' estimates of extent. Thus, filled and unfilled extent figures were presented as though viewed behind a slit moving to-and-fro. The task consisted of forced choice comparisons using the staircase method to estimate the point of subjective equality (PSE) for nine stimulus combinations: three levels of density (2, 6, or 10 vertical lines) and three velocities.

It was predicted that, consistent with the results obtained in Experiment 1, faster presentation rates would yield under-estimation of spatial extent relative to slower presentation rates and that unfilled extents would yield under-estimation relative to filled extents.

Method

Observers

Nineteen observers, ranging in age from 19 to 35 years, participated in this experiment. Participants were recruited primarily from undergraduate psychology classes and were paid for their participation. The observers reported normal or corrected-to-normal visual acuity.

Design

The task in this experiment consisted of width judgements obtained with a modified method of limits. Three levels of the Density condition, in which the test stimulus consisted of 2, 6 or 10 evenly spaced vertical lines, were combined with three presentation rates: slow, medium and fast. Each of nine test stimulus combinations was presented in one ascending and one descending staircase, giving altogether 18 series. Each observer completed all 18 staircase series, in a 3(Density) by 3(Velocity) repeated measures design.

Stimuli and Equipment

Equipment consisted of a Macintosh LC II computer and 12" RGB monitor, using HyperCard 2.0, MacroMind Director and MacroMind Accelerator (version 3) software. The stimuli were generated using the Director and Accelerator programs and presentation rates and sequences were controlled with the HyperCard program. A chin rest was used to maintain a constant viewing distance of 45 cm from the computer screen, giving a visual angle of 31 degrees for the diagonal of the illuminated area of the screen.

The stimuli consisted of sets of identical vertical lines placed horizontally (see Figure 6). The width between the outermost lines of all test stimuli was the same. Test stimuli were presented in sequence, as though viewed through a moving slit, oscillating horizontally to and fro over the extent of the stimulus. The stimuli, when entirely visible, subtended a visual angle of 10.1 x 1.5 degrees. The presentation rates were approximately as follows: slow condition, 3 seconds for one complete pass over the stimulus extent in one direction; medium, 1.5 seconds per pass; and fast, 0.75 seconds per pass. The comparison stimuli appeared

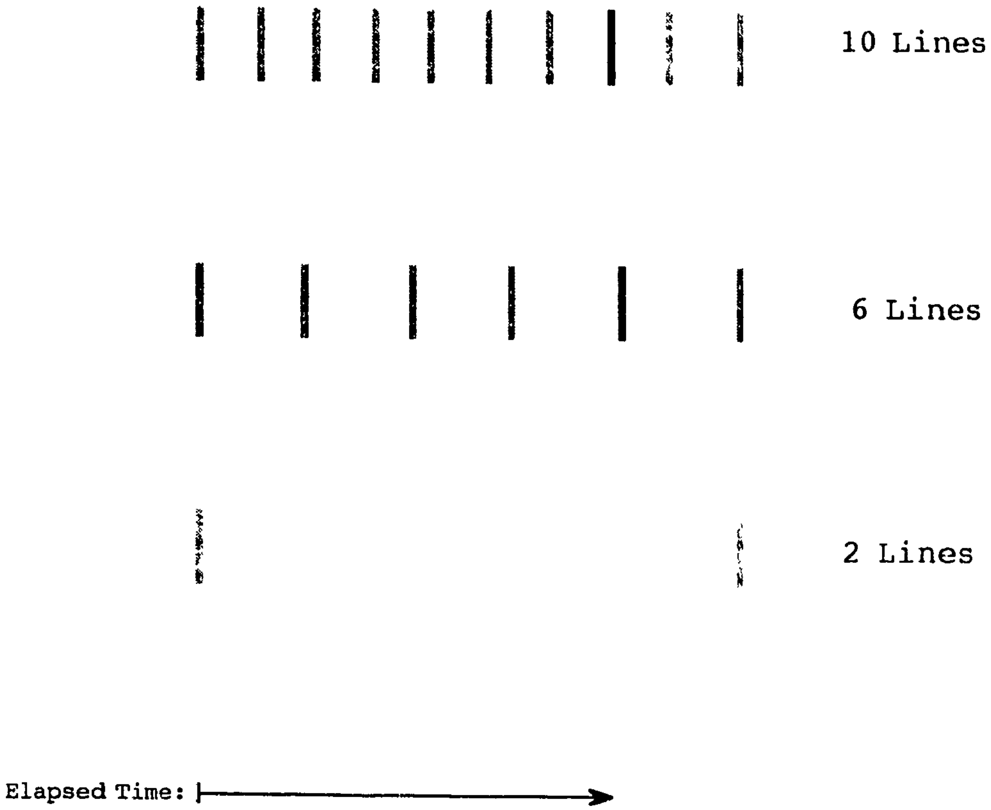


Figure 6. Three levels of Density stimuli presented sequentially. Shading indicates that only one element is visible at a time.

at the bottom of the screen and consisted of 2 vertical lines separated by varying widths, ranging from 4.6 to 15.4 degrees of visual angle.

Procedure

The observers were instructed in the use of the computer's mouse and given a practice staircase run. Each staircase series consisted of repeated trials in which observers compared a test stimulus against a comparison width demarcated by two vertical lines. On each trial, the test stimulus was presented at one of five positions on the computer screen and the comparison stimulus (2 lines) was centred at the bottom of the screen and present at the same time as the test. The observers viewed the two stimuli for as long as they wished and interrupted viewing by pressing the space key. At that point, the computer screen cleared and two buttons marked "Longer" and "Shorter" appeared at the bottom of the screen. Observers were instructed to enter their responses according to whether they thought that the distance between the two comparison lines _appeared_ longer or shorter than the distance between the two outermost lines of the test stimulus.

On the first trial of a descending staircase series, the comparison stimulus consisted of two vertical lines separated by 15.5 degrees of visual angle. If the observer judged this to be longer than the test stimulus, then comparison for the following trial was shorter, and so on. The ascending staircase began having a comparison stimulus width of 4.6

degrees of visual angle. Step sizes began at 1.5 degrees until three reversals of direction were made, after which the comparison width changed by 0.5 degrees. The staircase series ended when 15 reversals of judgement were made. The width of the comparison stimulus was recorded for each response. The order of presentation of the 18 staircase series was random for each observer.

The testing session was completed in approximately two hours with four short rest periods occurring at regular intervals.

Results

The data were first treated by averaging the comparison widths of the last 15 trials of the ascending and descending staircases for each velocity/density combination. For purposes of data analysis, these 15 scores were averaged, yielding 9 comparison widths (estimates of test stimulus), one for each velocity/density combination. These results are presented in Figure 7 and in table form in Appendix 3. As can be seen, perceived width tends to increase with slower presentation rates and, contrary to prediction, the width of the unfilled extent was perceived as wider than that of the highest density extent.

A 3 (Velocity) x 3 (Density) repeated measures analysis of variance was carried out. Significant main effects were obtained for both Velocity, $F(2,36) = 37.4$, $p < .001$, and Density, $F(2,36) = 8.58$, $p < .001$. The interaction was not significant. Post-hoc analysis using Tukey's H.S.D.

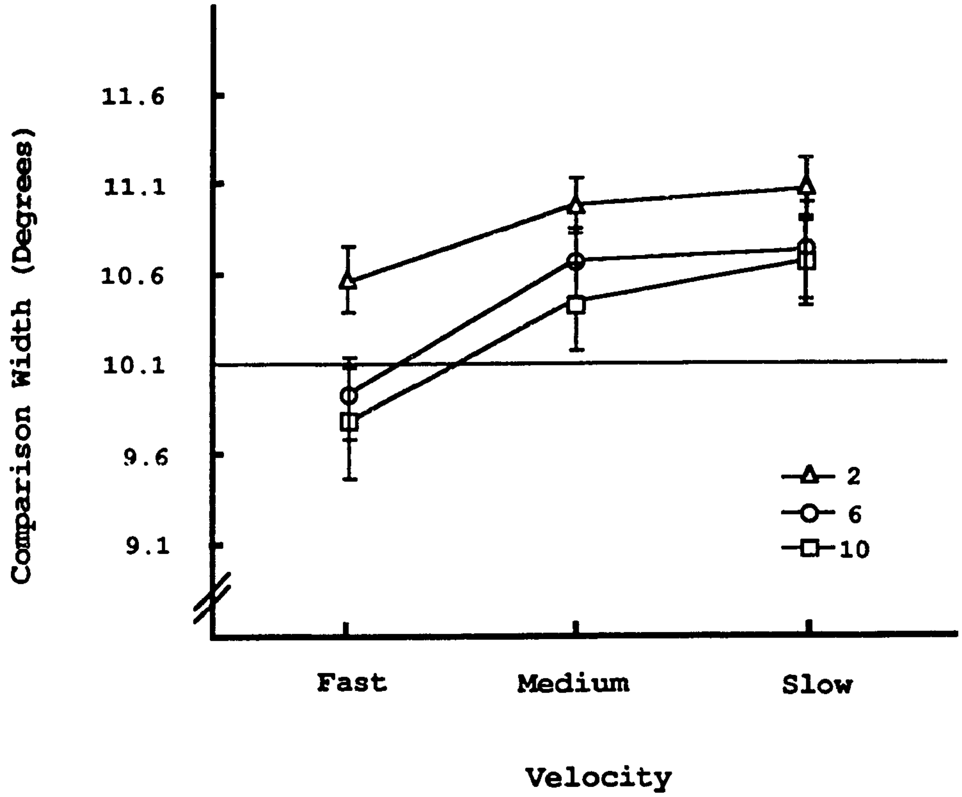


Figure 7. Mean Estimates Of Points Of Subjective Equality For Nine Stimulus Combinations Of Velocity And Density. Dimensions In Degrees Of Visual Angle.

procedure demonstrated that the estimates of extent for the Fast condition were significantly shorter than those for the other two conditions ($p < .01$) and that the 2 Lines (empty space) stimulus was estimated as significantly wider than the 10 Lines or 6 Lines (filled space) conditions ($p < .05$).

Discussion

The predictions about presentation rate were supported in this experiment: faster rates of presentation yielded shorter estimates of extent while slower rates gave longer estimates of extent. However, contrary to predictions, PSEs estimated for filled extent figures were smaller than those for the unfilled figure, regardless of presentation rate. In fact, this reversal was quite consistent across observers. The density effect may depend on velocity as well as the manner of presentation, simultaneous or successive.

It was observed that when the lines making up the filled and unfilled extent figures are presented successively, but at faster durations, (.75 to 3 sec) as in Experiment 2, the direction of the distortion was reversed so that the unfilled extent is perceived as wider than the filled extent. When the presentation durations are somewhat slower, (2.5 to 4.5 sec) as in Experiment 1, we found that the filled extent was judged wider more often than the unfilled extent, the normal illusion of filled and unfilled space.

The relationship of velocity and density to spatial extent is apparently more complex than supposed at the outset of this study. Although it was thought that this would be an appropriate method to test the relationship of density and velocity to perceived spatial extent, the successive mode of presentation, at least at the presentation rates employed in this study, may disrupt the type of analysis that may occur under other viewing conditions.

Informal, pilot testing revealed that there may be conditions in which the illusion may reverse, particularly when whole Oppel-Kundt figures are presented for a duration that is very brief, say, less than 100 ms. Therefore, the following experiment attempted to verify that the filled-unfilled extent illusion can reverse with brief viewing times and that the illusion gains strength with prolonged viewing.

Experiment 3

This study assessed the possibility of a time-dependent function for visual processing of spatial information. Based on informal pilot testing, it was hypothesised that, when the full Oppel-Kundt figure is presented with a very brief exposure, this would have the effect of precluding over-estimation of the filled extent or that the direction of the typical effect might be reversed (i.e., unfilled component appears wider than filled).

In addition to the effect of stimulus duration, the role of eye movements in the perception of the illusion was investigated. In Experiments 1 and 2, no attempt was made to control or monitor eye movements, except with sequential presentation of stimuli. In order to assess the role of fixation, the present study employed two viewing conditions, one in which a fixation point was present throughout the stimulus presentation and another in which there was no fixation point.

The design of the present experiment consisted of two factors, duration and viewing condition. The format of the study was a paired comparison task in which observers compared the filled and unfilled components of the Oppel-Kundt figure at two presentation durations, with and without instructions to fixate steadily. In all conditions, observers judged which of the components in the figure appeared wider.

Method

Observers

Ten observers participated in this experiment: 5 males and 5 females, ranging in age from 18 to 35 years, reporting normal or corrected-to-normal vision. Observers were paid for their participation.

Stimuli and Apparatus

The stimuli consisted of three arrangements of the Oppel-Kundt figure where the filled and unfilled components were displaced vertically and oriented horizontally (see Figure 8). From the observers' viewing position of 63.5 cm from the screen, the stimuli, including both filled and unfilled components, occupied 5.9 x 4.1 degrees of visual angle. The fixation point, when present, was located at the centre of the stimulus, mid-way between the filled and unfilled components. All stimuli were presented at the centre of the computer screen; on half of the trials, the filled component was positioned above the unfilled and, on the other half, the filled component was positioned below the unfilled. The stimuli were presented for two durations: a Short Duration of approximately 32 ms., and a Long Duration of 3 seconds. Therefore, there were four test stimuli in which the filled and unfilled components spanned physically equal extents. There were eight distracter stimuli in which the unfilled component was either wider or narrower than the filled component by ± 0.72 degrees, presented at two positions and two durations.

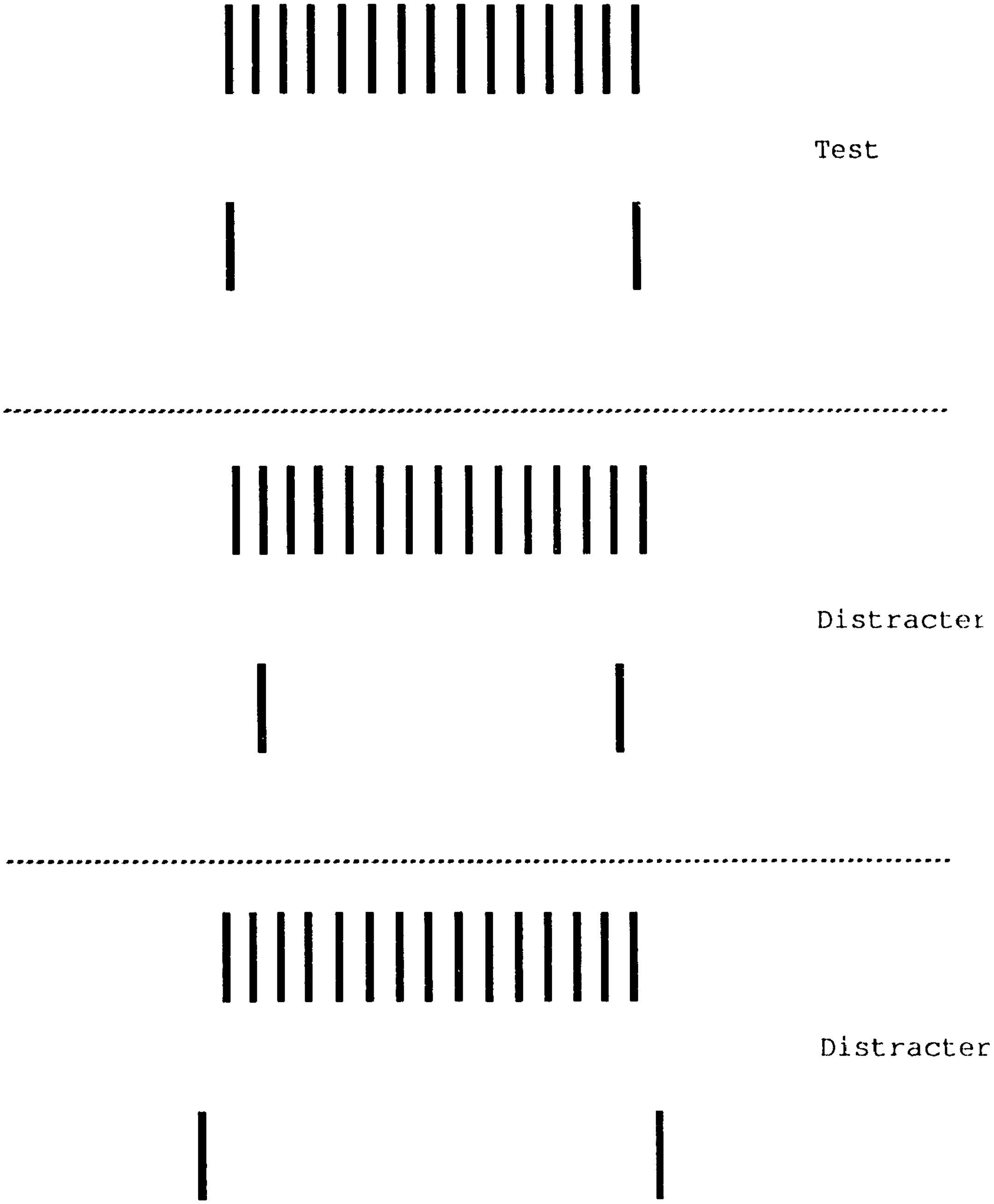


Figure 8. Test And Distracter Stimuli For Experiment 3.

Equipment consisted of a Macintosh LC II computer and 12" RGB monitor, using HyperCard 2.0, MacroMind Director and MacroMind Accelerator (version 3) software. The stimuli were generated using the Director and Accelerator programs. Presentation rates and sequences were controlled with the HyperCard program. A chin rest was used to maintain a constant viewing distance of 63.5 cm from the computer screen, giving a visual angle of 23 degrees for the diagonal of the illuminated area of the screen. Luminance values for the screen and stimuli are given in Appendix 7.

Procedure

The observers were instructed in the use of the computer mouse which they used to indicate their responses. Instructions were presented on the screen and reviewed verbally before beginning. The procedure for the No Fixation trials was that a sound marked the beginning of a trial followed by an "x" which allowed the observer to orient their gaze so as not to miss the short duration stimulus. The "x" appeared for 1 second in the centre of the area where the stimulus would appear, followed by a blank screen for 1 second, followed by the onset of the stimulus. After the stimulus disappeared, the observer indicated whether the filled or unfilled portion appeared wider by selecting the appropriate button at the bottom of the screen. Observers were reminded to base their judgements on the appearance of the stimulus.

In the Fixation condition, the observers were instructed that a tone would sound to mark the beginning of a trial. A small fixation point (4 pixels square) was visible on the screen throughout the Fixation block of trials. After a pause of 1 second, the stimulus was presented. The observer was instructed to gaze steadily at the fixation point for the duration of the stimulus. In order to control the influence of afterimages on succeeding trials, particularly in the Fixation block, a 4 second delay was allowed between trials and a 10 second pause was allowed between each block of 8 trials in which the observer was instructed to look around the room. After testing was completed, observers were asked whether they were aware of the persistence of afterimages into succeeding trials. None of the subjects reported awareness of afterimages persisting into subsequent trials.

The trials were presented in two blocks: the Fixation condition, in which there was a fixation point present for the duration of the stimulus presentation, and the No Fixation condition in which there was no steady fixation required. The order of presentation of the blocks was counterbalanced for observers.

In each of the Fixation and No Fixation blocks, there were 160 trials, including test and distracter trials. On half of the trials, the filled and unfilled components were physically equal. These test trials consisted of 40 short duration and 40 long duration presentations, counterbalanced for orientation (i.e., filled up or down). On the distracter trials, the stimuli were drawn randomly from a pool of eight. These stimuli varied in duration and orientation and were designed so that the unfilled component was either wider or narrower than the filled component. Within each viewing condition, trials were organised so that each of 20 blocks of eight trials contained four test and four distracter trials in random order. The four test trials consisted of one each of the duration x orientation conditions. The total of 320 trials were generally completed in 1 to 1.5 hours.

Results

Mean percentages of "filled = wider" responses for Long and Short durations in the two viewing conditions (Fixation, No Fixation) are presented in Figure 9 and in table form in Appendix 4. A 2(Duration) by 2(Viewing Condition) analysis of variance with repeated measures on both factors was carried out on the percentages of "Filled" responses. There was a significant main effect of Duration, $F(1,9) = 64.08$, $p < .001$, indicating that the filled component was selected as appearing wider significantly more often in the Long Duration than in the Short Duration condition, overall. There was neither a significant main effect of Viewing Condition nor a significant interaction of Duration and Viewing Condition.

Eight of the 10 observers had percentages of "Filled = Wider" responses less than 50% in the Short Duration/No Fixation condition. The sign test was applied to see whether the proportion of observers showing reversal of illusion,

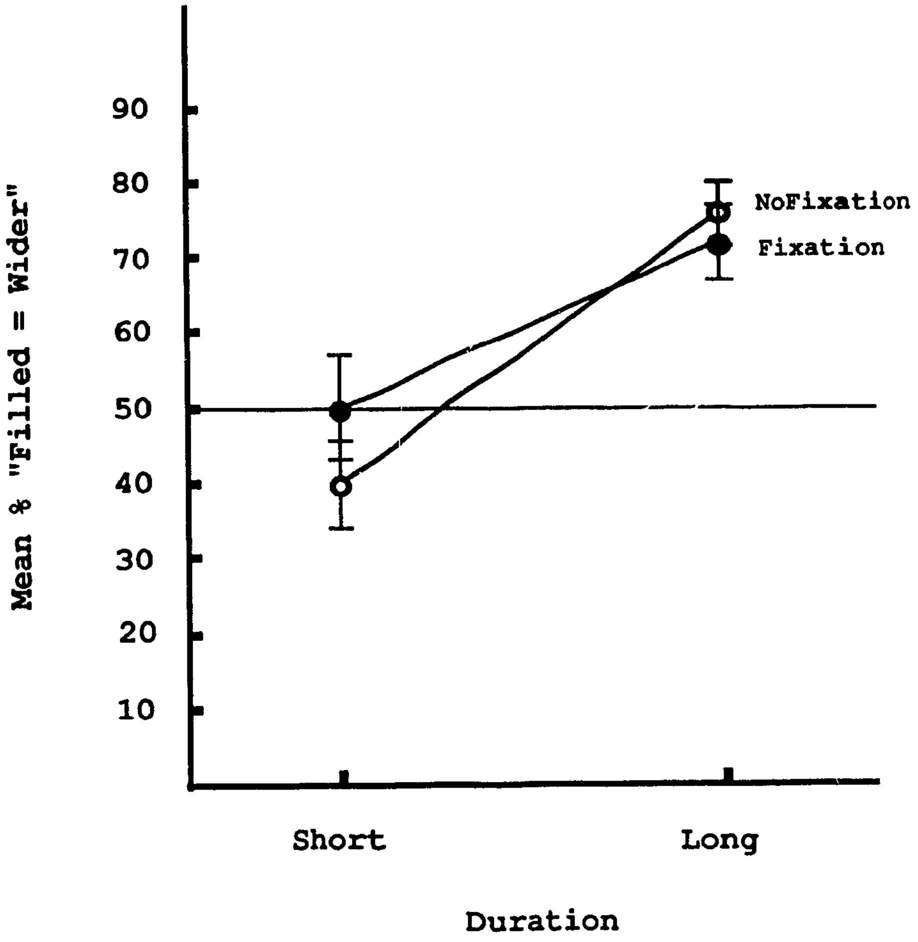


Figure 9. Strength Of Oppel-Kundt Illusion With Long (3 sec) And Short (32 msec) Presentation Duration

0.8, was significantly greater than 0.5. It was not, z = 1.58, $p > .05$, using a correction for continuity.

Discussion

The main finding of interest is that when the Oppel-Kundt illusion is presented at a sufficiently brief duration, observers are significantly less likely to judge the filled portion as appearing wider than when the stimulus is available for inspection for a few seconds. This trend is generally present in both viewing conditions, but is a little stronger, though not significantly so, without fixation. In the No Fixation condition, there is a slight tendency with the short duration to reverse the direction of the illusion.

These results are consistent with those of Experiment 2 in which there was a reversal of the high (filled) and low (unfilled) density illusion effect when the stimuli were viewed as though through a moving aperture. In that experiment, there was no fixation present for the duration of the stimulus presentation and it was, therefore, most similar to the No Fixation condition in the present experiment.

The results of the present experiment support the argument that illusion strength is correlated with a temporal factor. At an early stage of visual processing, which is accessed at the 32 ms. duration, the illusion is not present or reversed. Given a longer duration, the stimulus is more fully processed and the illusion increases in strength.

Based on these data, it was necessary to modify the model time/density functions shown in Figure 2 to show that, very early in processing, the apparent width may be either unaffected by the density factor or decreased by it. In other words, the time/density functions may cross. Further investigation was needed to examine this trend in greater detail, using a range of density stimuli and presentation durations. Preliminary pilot testing was carried out in which three Oppel-Kundt figures differing in filled density (4, 10, or 16 lines) were presented for durations ranging from 16 ms. to 1 second. The subjects indicated which component, filled or unfilled, appeared wider. The results showed more clearly that the illusion reversed for very brief durations. However, it was observed that the way in which the three density functions related to each other may be non-monotonic. Therefore, the next two experiments were conducted to shed light on these trends, beginning with an attempt to show how stimuli of different density are related in apparent width.

Experiment 4

As mentioned above, one aspect of the model in Figure 2 that possibly needed revision was the behaviour of the density functions relative to each other. The density functions had been arranged somewhat arbitrarily as though they followed a monotonic function relative to one another. Therefore, in preparation for Experiment 5, it was necessary to establish how these filled components differed in apparent width in order to predict how the different time/density functions would relate to one another. The stimuli were presented on paper and with ample time to examine the figures.

The purpose of this experiment, then, was to assess the relative widths of filled extent figures of various densities in order to interpret the results of other experiments in this series.

Method

Observers

The observers were 33 undergraduate psychology students enrolled in an Introduction to Psychology course. There were 18 females and 13 males, ranging in age from 18 to 40 years, with a mean of 21.3 years. Two observers declined to indicate either age or sex. The observers participated on a volunteer basis during class time and were not paid.

Stimuli and Apparatus

Testing booklets containing instructions, five practise trials and 72 test trials were made for group administration.

A blank white card was used by each observer to prevent the stimuli from the previous trial from showing through the paper. Nine stimuli of equal dimensions consisted of varying numbers of evenly spaced vertical line elements, ranging from 2 to 28 (see Figure 10). Each page of the booklet measured 21.5 x 14 cm. and bore two stimuli appearing one above the other and offset horizontally. The stimuli appeared with the vertical lines arranged horizontally across the wider extent of the page. The pages of the booklet were bound by two metal rings on the longer side of the page.

Design

The method of paired comparisons was used in which each of nine stimuli was compared with every other. Observers indicated which appeared wider. The 36 pairs were presented twice to each observer, counterbalancing the stimulus positions on the page.

Procedure

Testing took place in the classroom at the beginning of an early morning class. The experimenter read the instructions aloud and made sure the observers understood the procedure as well as how to use the booklets. The booklets were placed on the table blank-side-up with the bound edge nearest them. The experimenter sounded the beginning of each trial and the observers turned over the page towards them, exposing the two stimuli. The observers examined the stimuli and indicated which appeared wider by writing a "W" on or beside the appropriate stimulus. When the next trial was

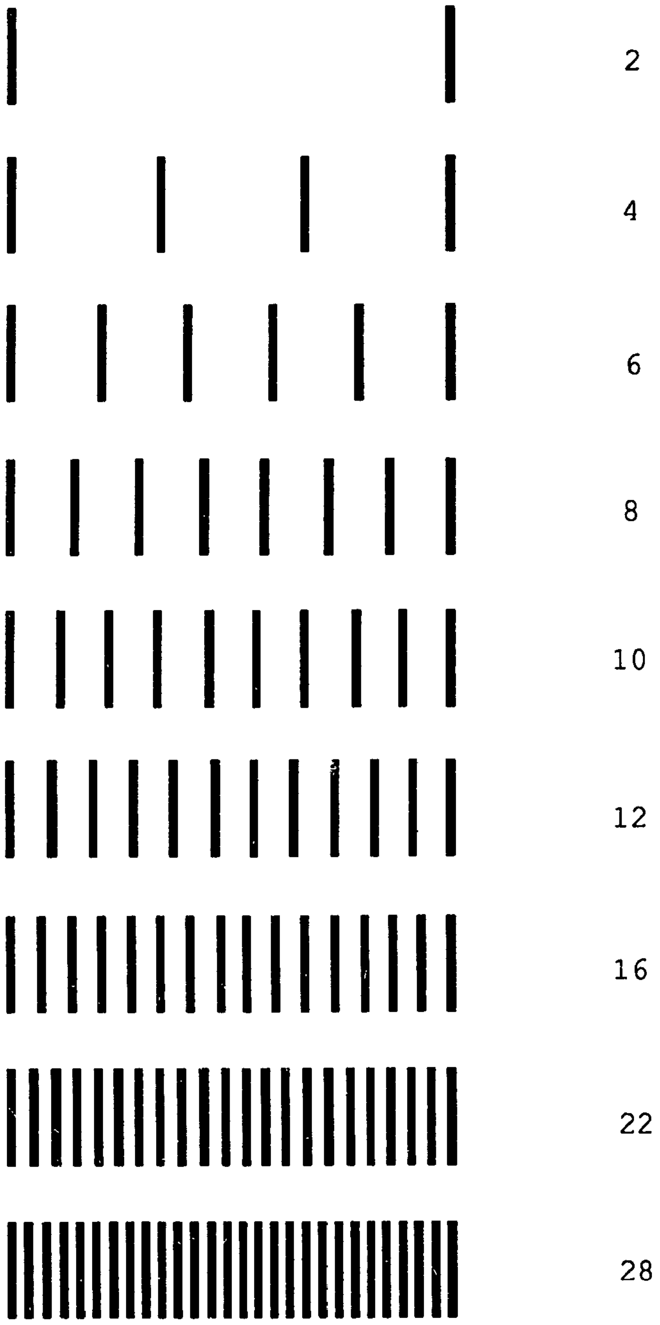


Figure 10. Nine Density Figures For Pair Comparison Task In Experiment 4

sounded, the observer covered the page with the blank card and turned over the next stimulus page. It was emphasised in the instructions that the observers were to base their judgement on their impression of which appeared wider, and not to attempt to measure the stimuli by some physical means (e.g., ruler, thumb, pencil, etc.). Observers were told that they had to guess when they were uncertain.

The trials were sounded at intervals of 5 seconds. There were five practise trials, followed by 72 experimental trials. There was a brief pause half-way through the experimental trials. The entire experimental session, from distributing the materials to collecting them, was accomplished within 20 minutes.

Results

Each of the 36 stimulus pairs was judged twice by 33 observers, giving a total of 66 judgements per pair. These data are presented in a table in Appendix 5 in which each cell gives the proportion of responses the "test" stimulus (columns) was judged wider than the comparison (rows). Note that the row showing the distribution of proportions obtained for all densities compared with Density 2 can be compared with the results of other experiments in which filled and unfilled extents are compared for different exposure durations.

The data were analysed using the pair comparison scaling method described by Guilford (1954) to determine relative subjective scale values for each of the density stimuli and to assess the internal consistency of the data. The scale values obtained from the proportion matrix are presented in Figure 11. Note that the scale values of width are in standard z units and not proportions. These values indicate a non-linear trend for subjective width according to stimulus density.

The test of internal consistency was carried out to determine whether the obtained distributions for the stimuli meet the assumptions of normality, unidimensionality and equal standard deviations. The matrix of obtained proportions were compared, using a Chi-square test, with the matrix of standardised values we would expect when the assumptions are upheld. The obtained value of $\chi^2 = 28.7$, $df = 28$, $p > .05$ means that the null hypothesis is retained and we assume that the above assumptions were not violated.

Discussion

The major finding of this experiment is that the relationship between density and perceived extent is indeed a non-monotonic function such that, at least for the stimuli employed in this experiment, subjective width increases as a function of the number of lines up to about 12 to 16 lines, after which subjective width decreases.

One problem with the procedure in this experiment is that, while a fairly naturalistic viewing situation, we cannot know precisely how long the stimuli were viewed by each subject for each stimulus condition. The trials were signalled at intervals of 5 seconds, but some of this time

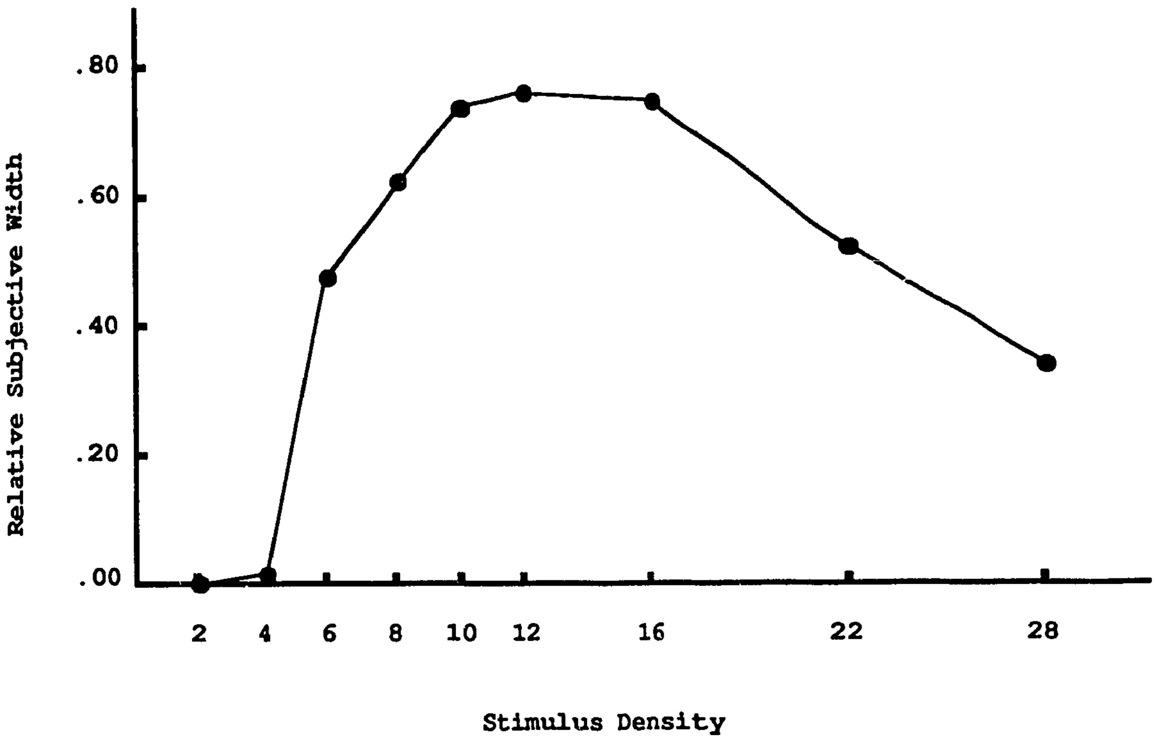


Figure 11. Relative Subjective Width Ratings of Nine Density Figures

was consumed by the turning of pages, some for visual orienting and some for responding. It can be assumed that the opportunity for viewing was at least 3 seconds, sufficient time for the maximum illusion effects to be reached.

Of secondary theoretical interest is that for those stimuli in which unfilled space is compared with filled space (Density 2 compared with every other) a non-linear trend was obtained that has its peak at Density 10. This finding has implications for predicting the outcome of the following experiment since the comparison is similar to that made for the Oppel-Kundt figures used in Experiment 3 and to be used in Experiment 5. The next experiment sought to follow the progress over time of the filled-unfilled extent illusion comparing three different density stimuli.

Experiment 5

The purpose of this experiment was to obtain time/density functions for three Oppel-Kundt figures, varying in filled density. Referring to the findings of Experiment 4, filled-unfilled extent arrangements were selected that appeared to sample sufficiently different subjective widths, namely, filled components containing 4, 10 and 22 lines. Seven stimulus durations were employed, ranging between 16 ms. and 1 second. Pilot testing indicated that these presentation times would be sufficient to follow the course of illusion development from as early as possible, given equipment limitations, until the illusion strength would likely reach its peak. It was predicted: 1) that the density functions would be related to one another in a way consistent with the results of the relative subjective width function, at least at the point of the longest presentation duration; and 2) that, at the briefest durations, illusion strength would be nil or reversed.

Method

Observers

Ten observers participated in this experiment, 6 males and 4 females, ranging in age from 18 to 35 years, reporting normal or corrected-to-normal vision. Observers were paid for their participation.

Stimuli and Apparatus

The stimuli consisted of three arrangements of the Oppel-Kundt figure where the filled and unfilled components were displaced vertically and aligned horizontally. The filled portions of the figures included 4, 10 or 22 evenly spaced vertical lines, thus varying density (see Figure 12). From the observers' viewing position of 75 cm from the screen, the stimuli spanned about 5 x 3.5 degrees of visual angle. The stimuli were presented in two positions, filled above unfilled or filled below unfilled. Therefore, there were six test stimuli in which the filled and unfilled components spanned physically equal extents. There were 12 distracter stimuli in which the separation of the lines of the unfilled component was either wider or narrower than the extent of the filled component by ± 0.72 degrees. The distracter stimuli were similarly constructed to those presented in Figure 8 of Experiment 3. The presentation durations were 16, 32, 50, 100, 200, 500 and 1000 ms.

The apparatus included a Macintosh LC II computer and 12" RGB monitor, using HyperCard 2.0, MacroMind Director and MacroMind Accelerator (version 3) software. The stimuli were produced using the Director and Accelerator programs and presentation rates and sequences were controlled with the HyperCard program. A chin rest was used to maintain a constant viewing distance from the computer screen, giving a visual angle of 19.8 degrees for the diagonal of the illuminated portion of the screen. Luminance values for the screen and stimuli are given in Appendix 7.

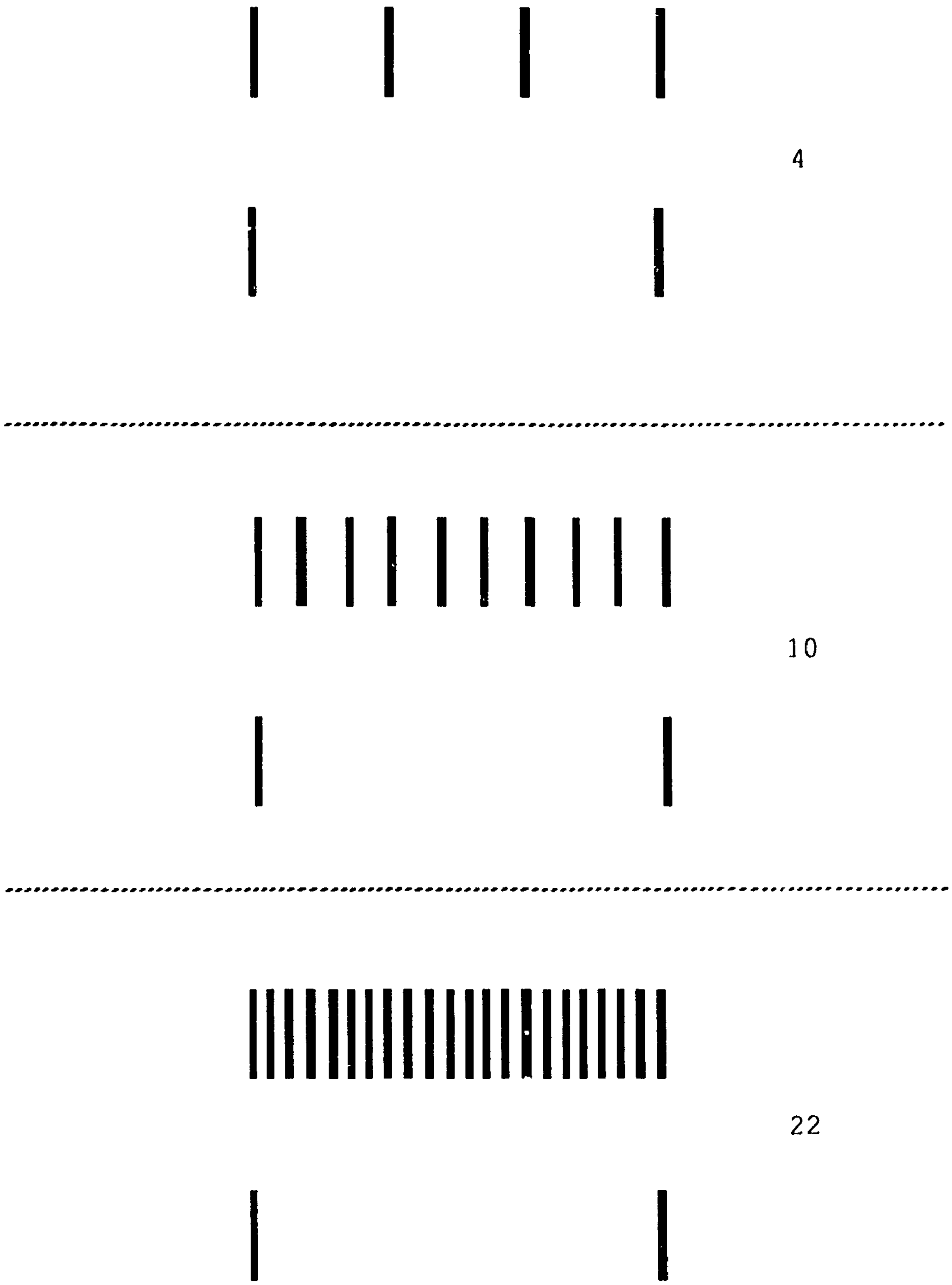


Figure 12. Test Stimuli for Experiment 5.

Procedure

The procedure of this experiment was similar to that of Experiment 3. The observers were instructed that a tone marked the beginning of a trial, following which an "x" appeared, centred in the region where the stimulus would appear. The purpose of the "x" was only to orient the observer so as not to miss the stimulus on the brief presentations. They had no instructions to fixate throughout the presentation of the stimulus. Following a pause of 1 second, the stimulus appeared. Observers were instructed to look at the stimuli for as long as they appeared on the screen. After the stimulus offset, the observer indicated whether the filled or unfilled portion appeared wider by selecting the appropriate button at the bottom of the screen. The observers were instructed to base their judgements on which stimulus appeared wider.

In all, there were 840 test trials in which the filled and unfilled components were physically equal (3 densities x 7 durations x 40 trials) and an equal number of distracter trials in which the components were physically unequal. Test and distracter stimuli were presented in random order, counterbalanced for orientation, within 40 blocks. The blocks were divided between two testing sessions and four rest pauses of 2 to 3 minutes were taken each session to minimise the observer's fatigue.

Results

Mean percentages for observers selecting the filled component as appearing wider for the seven durations in the three density conditions are presented in Figure 13 and in tabular form in Appendix 6. Note that the data points for a filled density of 16 lines obtained for three pilot subjects who did not participate in the main study are shown in Figure 13 for interest: these are represented by the unfilled symbols and were excluded from data analysis. A 3(Density) by 7(Duration) analysis of variance with repeated measures on both factors was carried out on the frequencies of "Filled" responses. There were significant main effects of Density, $\underline{F}(2,18) = 44.28$, $\underline{p} < .001$, and of Duration, $\underline{F}(6,54) = 14.98$, $\underline{p} < .001$. Post-hoc Tukey HSD comparisons indicated that, overall, the filled component was seen as wider significantly less often for the Density 22 figure than the other two which did not differ ($\underline{p} < .05$). Comparisons carried out across the levels of the Duration condition indicated that, overall, percentage illusion for the 500 ms. and 1000 ms. conditions were significantly greater ($p < .05$) from all of the shorter durations which did not differ. Figure 14a shows the means collapsed across levels of Density and Figure 14b shows the means collapsed across Duration (excluding pilot data).

The interaction of Density and Duration was also found to be significant, $\underline{F}(12,108) = 2.15$, $\underline{p} < .02$. Post hoc comparisons of means using the Tukey HSD method are included in Table 1. Since the table of critical values only included

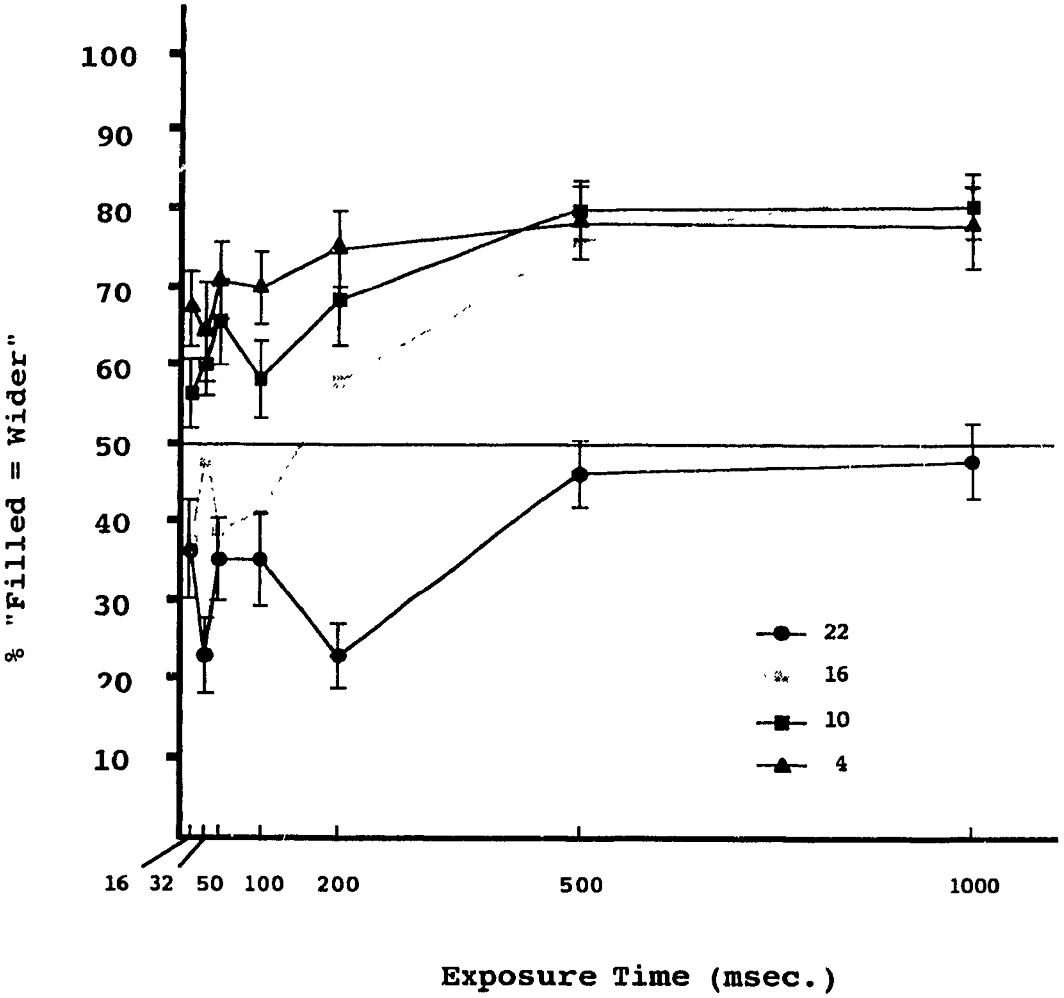


Figure 13. Percentage of "Filled is Wider" responses for 3 density stimuli at 7 presentation durations. Grey squares represent results from 3 pilot subjects where the filled density was 16.

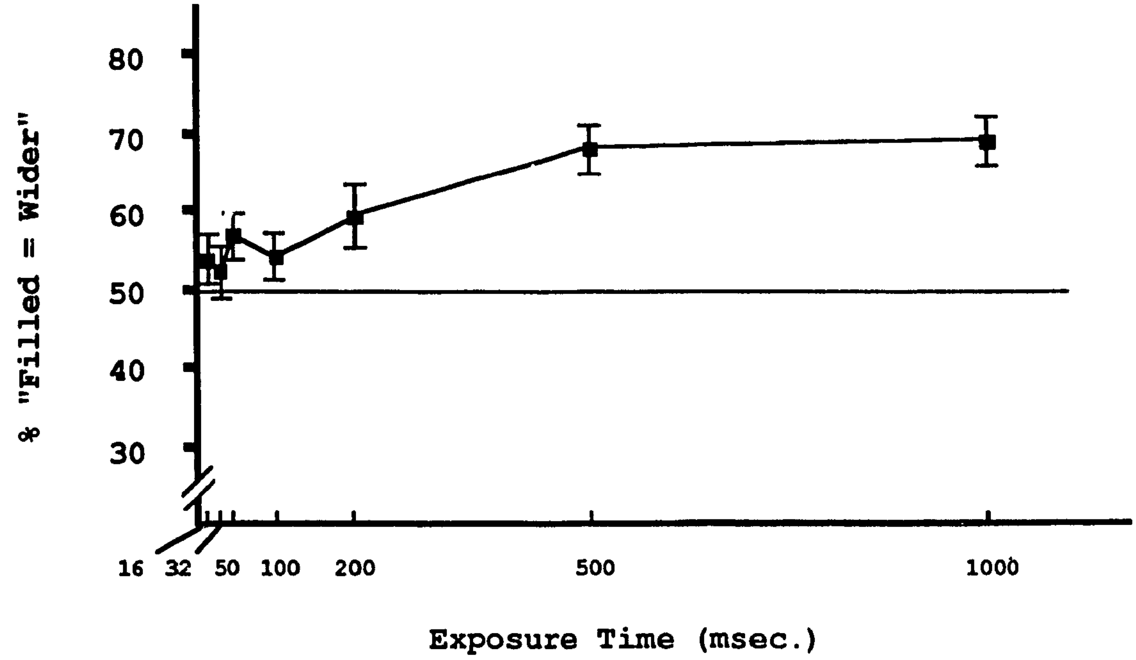


Figure 14a. Main Effect of Time Collapsed Over Density

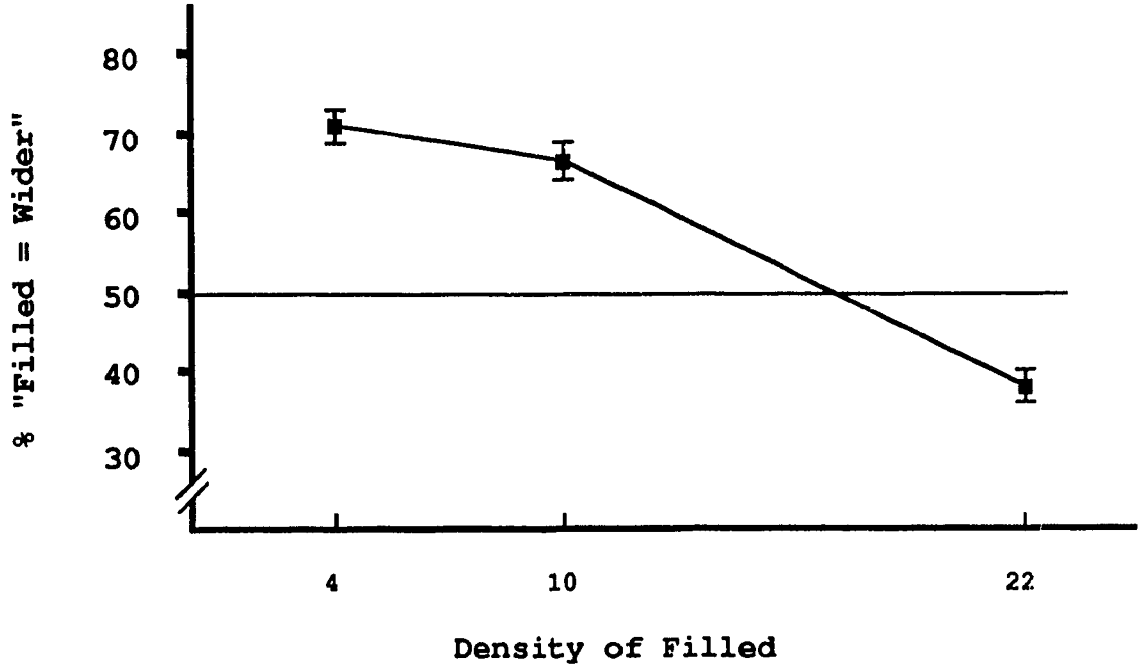


Figure 14b. Main Effect of Density Collapsed Over Time

Table 1

Paired comparisons between means for frequencies of "wider" judgements using Tukey's H.S.D. procedure. Stimulus conditions are listed by density, D, and duration, ms.

	D	ms																					
1	22	16	--																				
2	22	32	ns	--																			
3	22	50	ns	ns	--																		
4	22	100	ns	ns	ns	--																	
5	22	200	ns	ns	ns	ns	--																
6	22	500	ns	*	ns	ns	*	--															
7	22	1000	ns	**	ns	ns	**	ns	--														
8	10	16	**	**	**	**	**	ns	ns	--													
9	10	32	**	**	**	**	**	*	ns	ns	--												
10	10	50	**	**	**	**	**	ns	**	ns	ns	--											
11	10	100	**	**	**	**	**	**	ns	ns	ns	ns	--										
12	10	200	**	**	**	**	**	**	**	ns	ns	ns	ns	--									
13	10	500	**	**	**	**	**	**	**	**	**	**	**	ns	--								
14	10	1000	**	**	**	**	**	**	**	**	**	**	**	ns	ns	--							
15	4	16	**	**	**	**	**	**	**	ns	ns	ns	ns	*	*	*	--						
16	4	32	**	**	**	**	**	**	**	ns	ns	ns	ns	ns	**	**	ns	--					
17	4	50	**	**	**	**	**	**	**	**	ns	ns	*	ns	ns	ns	ns	ns	--				
18	4	100	**	**	**	**	**	**	**	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	--			
19	4	200	**	**	**	**	**	**	**	**	**	ns	**	ns	ns	ns	ns	ns	ns	ns	--		
20	4	500	**	**	**	**	**	**	**	**	**	**	**	ns	ns	ns	ns	**	ns	ns	ns	--	
21	4	1000	**	**	**	**	**	**	**	**	**	*	**	ns	ns	ns	ns	*	ns	ns	ns	ns	--
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21

* = $p < .05$

** = $p < .01$

criteria for comparisons of up to 20 means, the critical values for 21 means were derived by extrapolation (5.26 for *p* < .05; 5.99 for *p* < .01). One way to describe this interaction is that the perception of the different density stimuli were not equally affected by duration. The greatest increase in illusion strength was seen for the intermediate density (10 lines) and the least change over time was shown by the low density stimulus (4 lines).

Discussion

The results of this experiment demonstrated: 1) that illusion strength, and therefore, apparent width, develops over time; and 2) that Oppel-Kundt stimuli in which the filled portion has a high density will show a reversal of illusion with brief presentation durations of less than 500 ms.

However, the results did not completely conform to the predictions in two ways. First, it was expected from the results of Experiment 4 that the overall density values would be consistent with the subjective width function. That would mean that the values for stimulus density of 4 should appear less than those for the other two densities. This could mean that a one second duration is not long enough for full illusion strength to be reached for a density of 22 elements and, to a lesser extent, a density of 10 elements. In order to be consistent with the results of Experiment 4, in which up to 5 second inspection times were allowed, the lowest density stimulus (4 lines) would have to lose strength, a trend which would only show after one second duration. Though pilot testing had indicated that 1 second ought to be sufficient to allow full illusion strength, this was obviously not long enough for the highest density condition.

The second inconsistency was that, for very brief durations, there were still positive illusion effects for the intermediate and low density stimuli which indicates that, for the very brief durations, there may be an effect of visual persistence. Since a masking stimulus was not used in this design, it is possible that processing continued after the disappearance of the stimulus. The collapsed effects in Figure 14a show that, for durations of 200 ms. or less, the illusion strength does not change. If a masking stimulus were included in the design, it is possible that the data for the briefer durations would show more consistent reversal effects, or else the filled and unfilled component would appear more equal in width.

General Discussion

This series of experiments began with the premise that the perceived extent of a spatial array is determined jointly by stimulus density and time. In the general case, regardless of the manner of presentation, it was expected that perceived extent would vary positively with processing time and stimulus density and that these effects would be additive. A conceptual model, presented schematically in Figure 2 and mathematically in Equation 3, was proposed in which perceived extent is the result of a combination of both temporal summation and the magnitude of the retinotopic layout. The filled-unfilled extent illusion was used to test these predictions in visual perception.

Summary of Findings

The first general hypothesis was that varying the time and density of a stimulus should yield a set of linear functions similar to those presented in Figure 2. Perceived extent would increase as a function of both stimulus density and overall processing time. There was substantial support for this prediction: Experiment 1 showed that the combination of slow velocity and high density resulted in greater perceived extent than the combination of fast velocity and low density. Experiment 2 showed that slower presentation rates resulted in the perception of wider extents than did more rapid rates, when the subjects were making magnitude estimates. Although strong effects for density were demonstrated repeatedly, these were not related to perceived extent in a consistently positive direction, as predicted. In Experiment 1, the higher density array (10 lines) was associated with more "wider" judgements than the low density array (2 lines) while the opposite was found in Experiment 2 (i.e., magnitude estimates were smaller for 10 lines than for 2 lines).

Although all but one of the experiments involved relative judgements, it is assumed that magnitude estimates would yield very similar time-density functions to those obtained for illusion strength in the present experiments. In terms of the model presented in Figure 2, the data from these two experiments confirm the prediction that a linear function exists for processing time, but the results from Experiment 2 showed that the effect of density is not necessarily a simple linear function.

In each of the initial two experiments, there was no interaction of stimulus density and time which suggested that, within the parameters used, these components exert an effect on illusion strength that is additive. However, in order to understand why the stimulus density effect should reverse in the second experiment, it was noted that substantially faster presentation rates were employed in Experiment 2. In addition, the sequential nature of the presentation may have altered visual processing at different rates.

Therefore, in Experiment 3, the effect of presenting a variant of the Oppel-Kundt figure as a whole for very brief

(32 milliseconds) and for prolonged (3 seconds) durations was examined. These results confirmed that there are conditions under which the filled portion of the array (in this case, 15 lines) tends to be judged "wider" less often than the unfilled portion (2 lines). When the presentation duration was very brief, the typical illusion was non-existent, if not slightly reversed, whereas the prolonged duration resulted in the usual illusion effect. This indicates, then, that the typical illusion effect appears to develop with increasing processing time. As predicted from the model, there is some evidence that these relationships are similar whether or not scanning movements are somewhat restricted, as in Experiment 3, or somewhat controlled, as in Experiments 1 and 2.

Experiment 4 showed the relative subjective width function for a range of different densities, from 2 to 28 vertical lines, and helped to establish that the relationship between perceived width and number of elements of the stimuli employed in these experiments is non-linear. This was a necessary preparation for Experiment 5, in order to predict how a series of density functions might look in relation to each other.

Experiment 5 traced the development of the filled-unfilled extent illusion over time using seven exposure durations up to one second for figures of different stimulus density. Again, the results supported the hypothesis that apparent width increases with processing time. Illusion reversal was evident for high density stimuli at the very brief stimulus durations. The time/density functions did not entirely conform to the prediction based on the relative subjective width curve, found in Experiment 4.

Therefore, there was support for the general idea that the perceived extent of a visual array can be predicted from the density of the stimulus and from the duration of processing time, as roughly predicted in Figure 2. Through experimentation, this model was further refined to show that these density functions may cross at brief processing times to reflect reversal of illusion, depending on density.

It was also evident that the time and density relationship may be described by a trade-off function. This was along the lines of reciprocal energy relationships such as Bloch's Law for time and intensity and Ricco's Law for area and intensity which describe the effects of temporal and spatial summation. Different time and density values can be combined to maintain a constant perceived extent. Some support was found for these functions as can be seen in the results for magnitude estimates, where some time/density combinations resulted in similar estimates of extent. If a more comprehensive range of stimulus density values were included, the time-density reciprocity would be more completely understood.

Interpretative Comments

In general terms, the experimental results are supported by the differences in sensitivity and time course between the magnocellular and parvocellular pathways, that is, to the extent that stimulus parameters may invoke primarily one system or the other. However, these differences are only stated in terms of general tendencies, not absolute separations of function (see Zeki, 1993). When processing time is very brief, i.e., when the duration of the steady stimulus is very brief or the stimulus is presented rapidly in sequence, these stimuli are more effectively analysed by the magnocellular process in terms of their low-spatial frequency components. Prolonged, stationary displays permit analysis of the high-spatial frequency components by the parvocellular process. According to Livingstone and Hubel (1988), the magnocellular system tends to provide global information about the overall shape of the stimulus as well as to define borders and the grouping of elements, while the parvocellular system provides more detailed information about shape and texture.

At the outset of these experiments, the predictions were guided by the general heuristic model described by Equation 3. It was hypothesised that the first component of the perceptual distance formula, $v_{\psi}(t_0 + \Sigma\ t_n)$, represented primarily a temporal summation process, while the second term, k, defined primarily a preliminary retinotopic representation. The validity of these components can be assessed in light of the foregoing experimental findings and in terms of the parallel visual processes. It appears that a case can be made that the perceived extent due to the retinotopic representation, k, is affected by spatial summation processes and that this can account for reversals of illusion effect with brief presentation times.

The Role of Temporal Summation. The temporal summation portion of Equation 3 is supported in several of the findings of these experiments. Recall that the prediction stated that the overall amount of processing time would affect the perceived extent, regardless of the type of processing taking place. This was found, essentially, to be the case since the slower scanning rates in Experiments 1 and 2 were associated with greater perceived extent, regardless of density. Experiments 3 and 5 showed that illusion strength increases for Oppel-Kundt-like figures with increasing processing time.

There is also evidence that stimulus density affects processing time, and thus, perceived extent; however, this greatly depends on how much time is permitted for processing. The effect of density-induced time is less consistent such that very brief processing time leads to illusion reversal for high density stimuli. As long as processing time is long enough, temporal summation of density is possible. This leads to the possibility that the temporal summation component is carried out principally by the parvocellular process for the following reasons: 1) Prolonged exposure or slow scanning would favour this system over the magnocellular process; and 2) The parvocellular system is sensitive to high spatial frequencies, which is necessary in order to process density. However, temporal summation may begin very early since Figure 13 shows evidence that for stimuli with densities of 4 lines and 10 lines, temporal summation had been initiated by a duration of 16 milliseconds. Presentation of a masking stimulus could help clarify the time frame for temporal processing.

The Role of Spatial Summation. Evidence that the term, k, is moderated by spatial summation comes from the reversals of illusion with brief processing and high density. Higher density stimuli apparently require more processing time in order for temporal summation to be completed. The initial model did not predict reversals of the type where an unfilled extent appeared wider than a filled one as occurred in conditions where high density stimuli were presented at durations of 200 ms. or less, as in Experiments 3 and 5, or when presentation was sequential, as was the case in Experiments 2.

An experiment by Hunter and Sigler (1940) demonstrated that the thresholds for discrimination of black dots on a white background depended on the number of dots and the stimulus intensity. The more dots in the display, the greater the over-all energy (either increased intensity or longer duration) required for the subjects correctly to identify their number. Presentation durations ranged from 4 milliseconds to 4 seconds. At 4 ms. duration, the observers could identify up to 8 dots by increasing the intensity accordingly. When the displays contained more than eight dots, discrimination did not occur for durations less than 100 ms., regardless of intensity.

In the present set of experiments, the intensity of the stimuli was not adjusted for the different density stimuli. Following from Hunter and Sigler's results, given the brief durations employed in Experiments 3 and 5, it is possible that the highest densities may not be fully discriminated at durations of less than 100 ms. That means that the filled portion of the high density stimuli may be not seen as more dense, but as less bright. Therefore, the overall brightness of the stimuli likely plays a role in determining that portion of the perceived width of the stimulus contributed by k.

In order to understand this inter-relation of intensity and apparent width, we can consider Ricco's law which describes the energy relationship between intensity and area for thresholds. According to Ricco's law, threshold levels of stimulation are maintained by a reciprocal relationship in which the area (A) of receptor stimulation must increase in order to maintain a constant (c) energy level when intensity (I) decreases, and vice-versa. Piper's variation of Ricco's law, for stimuli subtending a visual angle greater than 2 degrees, is given by the following equation:

$$c = \sqrt{A} * I \tag{4}$$

This relationship is consistent with the spatial summation properties of the visual system in which the output from a number of receptors is pooled to a single retinal ganglion cell. If the intensity of the stimulus is stronger, then fewer receptors need be activated to produce a response in the ganglion cell. Conversely, if the stimulus is weaker, then receptor outputs must be pooled from a wider retinal area in order to reach threshold. Of course, spatial pooling may occur at higher levels of processing in the visual system, as well; however, it is convenient to describe the process in terms of retinal activity.

Ricco's and Piper's laws describe the convergence properties of perceptual systems. Although the application of these laws is to threshold levels of stimulation, they may be indirectly applicable to apparent area and intensity, at supra-threshold levels of stimulation.

In the present experiments, the comparisons were made between two stimulus components of the same physical dimensions differing in overall brightness. In such a situation, an extension of Ricco's law would be that the apparent width, k, of the stimuli will be determined by the spatio-topic layout of ganglion cells which is affected by convergence between the receptors and ganglion cells. When two stimuli differ in intensity but stimulate identical receptor areas, there will be a difference in the spatio-topic layout of ganglion cells reaching threshold through spatial pooling. More specifically, when a weaker stimulus is present, ganglion cells toward the edges of the region of stimulation will reach threshold with less frequency than when the higher intensity stimulus is present. The resulting difference in the perception of the size of the two stimuli will be that the brighter one appears greater in area. In further attempts to define the characteristics of k, it will be necessary to take into account the convergence properties of the visual system.

In Experiment 5, the result that, for the highest density stimuli with presentation times up to 200 ms., the unfilled extent appeared wider than the filled could be related to the tendency for higher density stimuli to be processed according to average brightness rather than detail and to the effect of spatial summation in affecting the apparent size based on the retinotopic area of ganglion responses.

While temporal summation may be primarily the result of sustained processing associated mainly with the parvocellular system, the scaled retinotopic extent defined by k may be largely due to transient processing supported primarily by the magnocellular system. The magnocellular process is more tuned to stimuli of brief duration, rapid motion, low spatial frequency, or high contrast. Thus, while the reversal of illusion was unexpected, it is nevertheless consistent with the model when viewed in terms of both temporal and spatial summation processes.

The density of the stimulus, then, tends to affect apparent size in two, somewhat antagonistic ways: 1) it expands apparent size by increasing processing time in the temporal summation process; and 2) it attenuates apparent size by decreasing the overall luminance of the stimulus.

The results from Experiment 4, in which a relative subjective width function was obtained for a range of filled space figures, given viewing durations of 3 to 5 seconds, can be interpreted in light of these two processes, as demonstrated in Figure 15. In the density range from 2 to 12 lines, the effect of the velocity-time component is greater than the attenuating effect of k with increasing density. Beyond the density range of 12 lines, the attenuation due to k leads to decreasing apparent width. The figure includes a prediction that increasing the density until the stimulus is a solid dark block will lead to that stimulus appearing narrower than the unfilled extent designated by a stimulus density of 2 lines. This prediction is consistent with Helmholtz's irradiation illusion in which a white area appears bigger than a black area of the same dimensions.

Figure 13 can also be interpreted in terms of spatial and temporal processing. The function describing the probabilities for the stimulus in which the filled portion consisted of 4 lines has for the briefest presentation durations very high certainty of illusion and shows, of all stimuli, the least increase in illusion with time. In fact, there is a slight indication that given even longer presentation durations, the probability of illusion is likely to decrease, perhaps to the level of 54% obtained in Experiment 4. The density difference between the filled and unfilled components of the stimulus is smallest, compared with the other stimuli and, therefore, the difference is least in terms of luminance contrast. Thus, the attenuation

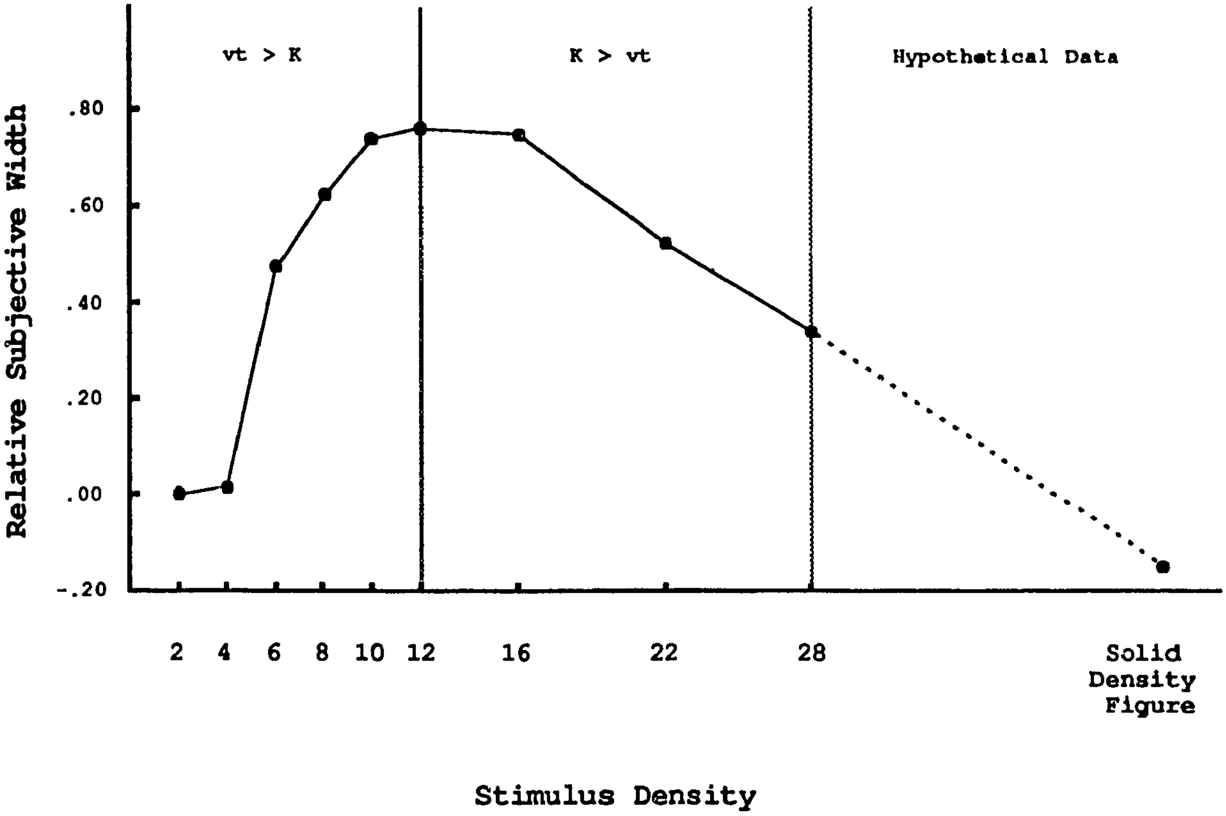


Figure 15. Revision of subjective width function indicating balance of temporal (vt) and spatial (K) processing contributions. Includes extrapolation of results to solid density stimulus.

of size due to k is least, and full illusion strength due to temporal summation is reached quickly.

The function for the stimulus with a filled component of 10 lines shows moderate presence of illusion with the briefest durations and shows the greatest increase in illusion probability over time of all three functions. Therefore, the increasing density attenuates perceived size initially, but contributes more to temporal summation over time.

The function for the stimulus having 22 lines in the filled component is clearly strongly attenuated in the early intervals, due to spatial summation, and the strength of the normal illusion due to temporal summation increases slowly thereafter. The full illusion strength for this figure is not reached in the 1 second presentation durations used in this experiment. It may be assumed that if 5 second inspection times were permitted with these stimuli, the resulting probabilities would be comparable to those obtained in Experiment 4.

Further Directions

More experimentation is needed in order to observe how temporal and spatial summation operate, and to test the validity of the present model for a variety of extent illusion figures. In particular, in would be important to examine the role of spatial summation and its supposed contribution to k. One obvious step would be to repeat Experiment 5, equalising the average brightness of the filled and unfilled components to see whether reversals of illusion would be eliminated, and to see whether there would be an increase in illusion strength in the positive direction.

Another important modification of Experiment 5 would be to use a masking stimulus to interfere with visual persistence, particularly for very brief durations. One manipulation would be to apply the masking stimulus immediately following off-set of the test stimulus. Insofar as a masking stimulus terminates processing time, there would be a clearer picture of how the illusion develops in the early stages of processing. Another manipulation would be to follow the progress of one Oppel-Kundt stimulus with one presentation duration, applying the masking stimulus after different inter-stimulus intervals.

There are a few ways in which further research could help to discriminate more clearly between the magnocellular and parvocellular processes in the analysis of these illusion figures. One is to take advantage of the magnocellular system's colour-blindness and present high and low density figures in equiluminant red and green. (In spite of Zeki's (1993) complaint, this may still be interesting to try.) Where figure and ground are equiluminant red/green arrangements, we would expect that the illusion would disappear with very brief durations, if the stimuli are even discernible. Only with prolonged presentation rates would the illusion gain strength and the lowest density stimuli would lose strength overall.

Another approach would be to present the stimuli as a series of brief flashes instead of as steady prolonged presentations with the expectation that this would pre-empt the parvocellular system. Using the same stimuli from Experiment 5, the illusion strength established in the briefest durations would hold true even after 500 milliseconds of total presentation. Moreover, the reversal of illusion evidenced for very high density stimuli would persist.

The results of these experiments can be interpreted adequately in terms of known structural processes related to the magnocellular and parvocellular pathways, and the predictions derived from the model appear to be supported by the data. It is clear that the perception of spatial extent develops with processing time according to particular stimulus features. The findings are consistent with the fact that the brain does not possess an absolute spatial metric, but one that is fluid and relative.

Some of the illusion explanations reviewed earlier in this paper contain some component of the time/density relationship proposed here. For example, eye movement theory suggests that the movement distance is responsible for perceived extent but fails to link this to processing time as a mediating factor. When processing time is acknowledged there is no need to assume efferent readinesses to account for the persistence of illusion in static displays. Both Piaget's centrations and Pressey's assimilation explanations give some account of what is defined here as density, but they allude generally to attentional factors rather than specifically to processing time.

To conclude, the estimation of spatial extent is an essential component of many perceptual activities, including recognising objects and mapping environments. Of course, the stimuli used in these experiments were very specific in configuration and it is infrequent that one encounters such designs in the real world, with the possible exceptions of, perhaps, a row of poplar trees in the Impressionist-era countryside of France, or picket fences. Nonetheless, the temporal dimension of size perception must certainly operate in the processing of other illusions of extent as well as in the perception of objects and spaces in the real world. It is hardly conceivable, then, that a theory of geometric illusion would be complete without taking into account processing time and density.

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Appendix 1

Stimulus combinations for Experiment 1.

Two levels of Velocity were combined with two levels of Density to make four stimuli. There are 16 possible paired comparisons, for which presentation order is important, shown below:

Stimuli:

High Density/Fast Velocity = HF
High Density/Slow Velocity = HS
Low Density/Fast Velocity = LF
Low Density/Slow Velocity = LS

Comparisons:

HF vs. HF
HF vs. HS
HF vs. LF
HF vs. LS

HS vs. HF
HS vs. HS
HS vs. LF
HS vs. LS

LF vs. HF
LF vs. HS
LF vs. LF
LF vs. LS

LS vs. HF
LS vs. HS
LS vs. LF
LS vs. LS

Appendix 2

Tables of Results from Experiment 1.

Velocity Effects, in which same-density stimuli are compared at fast and slow velocities. Mean proportion of wider judgements.

	Low Density	**High Density**	**Average**
Fast Velocity	.38	.48	.43
Slow Velocity	.62	.52	.57

Density Effects, in which high and low density stimuli are presented at the same velocity. Mean proportion of wider judgements.

	Fast Velocity	**Slow Velocity**	**Average**
Low Density	.42	.33	.37
High Density	.58	.67	.63

Velocity x Density Effects, in which two stimuli were compared differing in velocity and density. Mean proportion of wider judgements.

	Low Density	**High Density**
Fast Velocity	.25	.65
Slow Velocity	.35	.75

Appendix 3

Tables of Results and Analysis of Variance from Experiment 2.

Mean PSEs (in degrees of visual angle) for nine stimulus conditions, Experiment 2. Width of test stimuli = 10.1°. Standard errors in parentheses.

Density / **Velocity**	**10 Bars**	**6 Bars**	**2 Bars**
Slow	10.70 (.23)	10.75 (.23)	11.03 (.23)
Medium	10.43 (.23)	10.70 (.17)	10.98 (.17)
Fast	9.81 (.34)	9.93 (.23)	10.53 (.17)

Analysis of Variance Summary Table for Data of Experiment 2. (Based on data in centimetres).

Source of Variation	*df*	Sum of Squares	Mean Square	*F*	*p*
Subjects	18	46678.12	2593.23		
Density	2	3524.54	1762.27	8.58	.0009
Error	36	7390.90	205.30		
Velocity	2	7166.89	3583.45	37.40	.0000
Error	36	3449.29	95.81		
D x V	4	506.27	126.57	1.65	n.s.
Error	72	5520.09	76.67		

Appendix 4

Tables of Results and Analysis of Variance from Experiment 3.

Mean percentage of judgements in which the Filled component appears wider.

Condition	**Short Duration**	**Long Duration**	**Average**
NoFixation	39.8 (5.0)	76.3 (4.0)	58.0
Fixation	50.3 (6.0)	72.5 (5.0)	61.4
Average	45.0	74.4	

Analysis of Variance Summary Table for Data of Experiment 3.

Source of Variation	df	Sum of Squares	Mean Square	F	p
Subjects	9	.618	.076		
Fixation	1	.011	.011	1.57	ns
Error	9	.065	.007		
Time	1	.860	.860	64.08	.0000
Error	9	.121	.013		
F x T	1	.051	.051	4.30	ns
Error	9	.102	.012		

Appendix 5

Proportion matrix for judgements in which test stimulus appears "wider" than comparison.

	Proportion of "Test is Wider" Responses								
Test Comp	**2**	**4**	**6**	**8**	**10**	**12**	**16**	**22**	**28**
2	(.50)	.54	.74	.71	.83	.74	.73	.64	.65
4	.46	(.50)	.68	.68	.74	.68	.80	.73	.76
6	.26	.32	(.50)	.62	.67	.56	.65	.54	.38
8	.29	.32	.38	(.50)	.54	.53	.51	.51	.35
10	.17	.26	.33	.46	(.50)	.59	.51	.39	.38
12	.26	.32	.44	.47	.41	(.50)	.48	.35	.30
16	.27	.20	.35	.49	.49	.52	(.50)	.47	.26
22	.36	.27	.46	.49	.61	.65	.53	(.50)	.47
28	.35	.24	.62	.65	.62	.70	.74	.53	(.50)
Mean	**.324**	**.330**	**.500**	**.563**	**.601**	**.608**	**.606**	**.518**	**.450**

Appendix 6

Tables of Results and Analysis of Variance for Experiment 5.

Table of Mean Percentages and Standard Errors (in parentheses) for Experiment 5.

Duration (ms.)

Density	16	32	50	100	200	500	1000
22	36.5 (6.5)	33.5 (4.7)	35.5 (5.5)	35.5 (6.2)	33.5 (4.2)	46.3 (4.2)	48.0 (4.8)
10	56.5 (4.5)	60.5 (4.4)	65.0 (5.6)	58.3 (5.1)	68.5 (6.0)	80.0 (4.0)	80.3 (4.1)
4	67.3 (4.8)	64.5 (6.4)	71.0 (4.9)	70.8 (4.6)	75.3 (4.7)	79.8 (4.6)	78.5 (5.3)

Analysis of Variance Summary Table for Data of Experiment 5.

Source of Variation	*df*	Sum of Squares	Mean Square	*F*	*p*
Subjects	9	4379.95	486.66		
Density	2	7490.07	3745.03	44.66	.0000
Error	18	1522.41	84.58		
Time	6	1349.71	224.95	14.98	.0000
Error	54	810.95	15.02		
D x T	12	242.40	20.20	2.15	.02
Error	108	1013.79	9.39		

Appendix 7

Luminance Values for Experimental Stimuli.

Computer Screen:

White Background:	23.10 Ft.Lamberts
Black Lines:	00.00 Ft.Lamberts

Luminance of Stimuli (Filled Components) for Experiments 3 and 5.

Filled Portion	Luminance (Ft.Lamberts)	Luminance Ratio (Filled to Blank)
4 lines	21.75	.94
10 lines	19.30	.83
15 lines	17.10	.74
22 lines	13.60	.59

Note: These measurements were made with an EG&G Radiometer/Photometer (Model 550-1).