Brightness and contrast as cues to depth in the simulator display: cue combination and conflict resolution

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ABSTRACT:

When computer generated images are used for real-time display in simulator applications, much of the fine detail available from the natural world, or even from video-film, is not available to an observer. This lack of detail leads to a reduction in the number of sources of depth information (cues to depth) that are available to specify the layout of the displayed scene. Amongst the cues normally available are luminance gradients and luminance contrast gradients, each deriving from luminance differences between components of the displayed scene; however, in computer generated images, these two cues do not always conform to the intended natural world image, and can offer conflicting information.

While not referring explicitly to luminance gradients, Ames (1949) demonstrated that the brighter of two otherwise identical objects would appear nearer; his Demonstration 18 offering a negative luminance gradient similar to that arising in the natural world from atmospheric perspective. Similarly, Ross (1967, 1993) and O'Shea, Blackburn and Ono (1994) have shown a similar effect to Ames (1949), but with higher contrast replacing increased brightness, which they liken to the negative luminance contrast gradients that are also available in the natural world due to atmospheric perspective. The luminance gradient, and luminance contrast gradient cues are generally in accord when the scene background is light, but are in conflict where the background is dark.

The experiments reported here show that either gradient can function as a cue to depth, and hence to the spatial layout of a depicted scene, and that conflicts between them are
resolved in a way that takes into account the amount and type of other depth information available to an observer. Such a form of conflict resolution and cue combination is in accord with the separate items of depth information being processed either partly or wholly in parallel, so that the strength of each cue is determined by reference to the other available cues.

When applied to simulators using computer generated images, these results suggest that both users, and scenario designers, require an awareness of the possible effect of a change to any item of depth information, and in particular to depth information that has its origin in luminance differences between objects in the depicted scene.
DEDICATION AND ACKNOWLEDGEMENTS

This thesis is dedicated to the memory of my son

Jonathan Hone (1963 - 1991)

No work of this nature is done without the help and support of many people, in many different ways. These few words of appreciation may be inadequate, but are indeed from the heart.

First, I must thank my supervisor, Ian Davies; not only for his guidance and inspiration during the course of this research, but for giving me the opportunity to carry it out in the first place. Many other people within my Department have been involved, and I must acknowledge the technicians, notably Nigel Woodger for the precision with which he edited so many video-tapes, and my colleagues: Clare, Gina, Sarah, Korinna, Lynne, Ruhksana, Jörg and Paul.

Research involving simulators is only practical if a simulator is available: here, thanks are due to Mr. Mike Kelly and his section at the Army Personnel Research Establishment - now the DRA Centre for Human Sciences - at Farnborough, for making available the BEST Simulators, and for enabling me to see current advanced simulators in operation.

Finally, none of this would have been possible without the encouragement and total support of my wife, Deirdre, and our children Siobain, Alison and Jonathan.
# TABLE OF CONTENTS

## PREAMBLE

- PREAMBLE \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 1

## CHAPTER 1: Initial Experiments.

1. General Introduction \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 4
2. Experiment 1.
   2.1. Introduction \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 6
   2.2. Method \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 6
   2.3. Results \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 11
   2.4. Discussion \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 14
   2.5. Conclusion \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 15
3. Experiment 2.
   3.1. Introduction \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 18
   3.2. Method \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 22
   3.3. Results \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 28
   3.4. Discussion \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 31
   3.5. Conclusion \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 35
4. Overall Assessment \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 35

## CHAPTER 2: Simulators.

1. Introduction \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 36
2. A brief history \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 36
3. Producing the display \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 39
4. Presenting the display \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 42
5. Depth perception and the cues to depth \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 44
6. Information from luminance and contrast \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 47
7. Other limitations of CGI
   7.1. Texture gradients \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 51
   7.2. Field of view and the station-point \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 52
8. To improve the image \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 53
   8.1. Hardware improvements and developments \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 54
   8.2. Scene requirements and software \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 55
9. Conclusion \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( \ldots \) \( p \) 57
CHAPTER 3: Depth information on the monitor screen.

1. Introduction
2. Cues that specify flatness
3. Cues that specify depth
   3.1 Texture and texture gradients
   3.2 Height in the visual field
   3.3 Relative size and familiar size
4. Linear perspective in depiction
   4.1 The importance and limitations of perspective
   4.2 Information from perspective
5. Information from luminance
6. Aerial perspective
7. The validity of size judgements
8. From cue conflict to illusion
9. Cue combination
10. Conclusion

CHAPTER 4: The comparison task experiments.

1. General Introduction
   1.1 The task changes
   1.2 The information available
2. Experiment 3.
   2.1. Introduction
   2.2. Method
   2.3. Results
   2.4. Discussion
   2.5. Conclusion
3. Experiment 4.
   3.1. Introduction
   3.2. Method
   3.3. Results
   3.4. Discussion
   3.5. Conclusion
TEXT (Chapter 4 continued)

4. Experiment 5.
   3.1. Introduction
   3.2. Method
   3.3. Results
   3.4. Discussion
   3.5. Conclusion

5. General discussion.

CHAPTER 5: The brightness experiment.

1. Introduction
2. Method
3. Results
4. Discussion
5. Conclusion

CHAPTER 6: The moving object experiments.

1. Introduction
2. Experiment 7.
   2.1. Introduction
   2.2. Method
   2.3. Results
   2.4. Discussion
   2.5. Conclusion
3. Experiment 8
   3.1. Introduction
   3.2. Method
   3.3. Results
   3.4. Discussion
   3.5. Conclusion
4. Experiment 9
   4.1 Introduction
   4.2 Method
   4.3 Results
   4.4 Discussion
   4.5 Conclusion
CHAPTER 7: General discussion and conclusions.

1. Introduction ........................................... p 207
2. An overview of the results ......................... p 207
3. The effect of experimental instructions ........ p 211
4. Cue combination and cue conflict ................. p 212
5. The immediate implications ....................... p 214
6. Suggestions for future research ................. p 217
7. Conclusion ............................................. p 219

REFERENCES .............................................. p 221

APPENDIX: The BEST simulator ...................... p 234

TABLES:

CHAPTER 1: Initial Experiments.

Experiment 2.
1.1. Rearward displacements of the adjustable block .. p 29
1.2. Angular errors in setting the adjustment device .. p 31

CHAPTER 2: Simulators.

2.1. Depth cues and their potential for conflict on the monitor .. p 46
TABLES (continued)

CHAPTER 4: The comparison task experiments.

4.1. Information manipulations ........................................ p 98
Experiment 3.
4.2. Scene luminance variations for Experiment 3. .................. p 104
4.3.a Variable line judged longer than the comparison line 
(Order L-M-D) .............................................................. p 107
4.3.b Variable line judged longer than the comparison line 
(Order D-M-L) .............................................................. p 107
4.3.c Variable line judged longer than the comparison line 
(Control) ................................................................ p 108
Experiment 4.
4.4. Mean judgements: variable line longer than comparison line p 122
Experiment 5.
4.5. Mean judgements: variable line longer than comparison line p 133

CHAPTER 5: The brightness experiment.

5.1. Luminance values and aperture sizes ................................ p 159

CHAPTER 6: The moving object experiments.

Experiment 7.
6.1. Luminance values ...................................................... p 169
6.2. Error scores .............................................................. p 174
6.3. Means across subjects of the standard deviations ............. p 175
6.4. Judgements following change in luminance ...................... p 177
Experiment 8.
6.5. Positional error scores ................................................ p 188
Experiment 9.
6.6. Positional error scores ................................................ p 198
FIGURES:

CHAPTER 1: Initial Experiments.

Experiment 1.
1.1. Typical stimulus as seen by subject ... ... ... p 9
1.2. Possible effect of luminance differences ... ... ... p 10

Experiment 2.
1.3. Possible effect of luminance on angle ... ... ... p 20
1.4. Stimulus layouts for Experiment 2 ... ... ... p 23
1.5. Changes in screen luminance ... ... ... p 33

CHAPTER 2: Of simulators.
2.1 Screen luminance: change over time ... ... ... p 49

CHAPTER 3: Depth information on the monitor screen.
3.1. Single and two-point perspective ... ... ... p 69

CHAPTER 4: The comparison task experiments.

Experiment 3.
4.1. Typical stimulus as seen by subject ... ... ... p 103
4.2. Interaction: Line length and luminance order ... ... ... p 110
4.3. Interaction: Line length and background scene ... ... ... p 111
4.4. Interaction: Luminance order and background scene ... ... ... p 113

Experiment 4.
4.5. Interaction: Luminance order and line length ... ... ... p 125

Experiment 5.
4.6. Interaction: Luminance order and variable line inclination ... ... ... p 135
4.7. Interaction: Background scene and variable line inclination ... ... ... p 137
4.8. Interaction: Line length and line inclination ... ... ... p 138
4.9. Interaction: Luminance order and background scene ... ... ... p 140
4.10. Interaction: Luminance order and line length ... ... ... p 141
4.11. Interaction: Background scene and line length ... ... ... p 143
4.12. Interaction: Luminance order, background scene and line length ... ... ... p 144
4.13. Interaction: Luminance order, line length and inclination ... ... ... p 146
4.14. Interaction: Line length, inclination and background scene ... ... ... p 147
4.15. Interaction: Line length, luminance order and background scene ... ... ... p 148
FIGURES (Continued)

CHAPTER 6: The moving object experiments.

Experiment 7.
6.1. Equipment layout for Experiment 7 .......................................................... p 172
6.2. Standard deviations: means across subjects .............................................. p 176
6.3. Judgements following screen luminance change ...................................... p 178

Experiment 8.
6.4. Typical stimulus scene ............................................................................. p 184
6.5. Equipment layout for Experiment 8 .......................................................... p 186
6.6. Interaction: Scene and target location ....................................................... p 190

Experiment 9.
6.7. Typical stimulus landscape ....................................................................... p 195
6.8. Interaction: Moving object luminance and target location ...................... p 201
6.9. Regression plot: light and dark scene sets ............................................... p 202

PLATES:

Chapter 1:
Plate 1: The Adjustment Device. ................................................................. p 26

Chapter 3:
Plate 2: Atmospheric Perspective. ............................................................... p 78
PREAMBLE

Of all the senses - sight, touch, hearing, smell, etc - that tell us about the external world, sight is the most important. A young child wishing to deny the existence of something unpleasant will cover its eyes, and learning that the external world exists independent of our sight of it, is a critical stage in human development. It is not surprising that visual perception has attracted so much research using a variety of approaches. Sedgwick (1986) has distinguished seven such approaches, and stressed that these are as often complementary as they are opposed, and that any piece of research may often draw on more than one of them. Such will be the case here: the ecological approach associated with Gibson (1950, 1966) and the cognitive approach of, for example, Gregory (1970), Hochberg (1964) or Rock (1975) being intertwined throughout.

The fundamental difference between these two approaches is that the ecological view holds that the environment gives a complex structure to the light reaching the eye of an observer, and that this structure and the changes within it are sufficient to specify the observed portion of the external world; the cognitive approach has the observer processing such items of information as can be extracted from the retinal image to form a percept. Thus, Gibson (1966) refers to psychological invariants within the total flow of optical information, including texture gradients, brightness gradients and contrast gradients, and assumes that the observer is mobile within the environment; in contrast,
the cognitive approach is to seek to identify the individual components within the total array of information, and to establish how these build into a single percept. Where these individual components, or sources of information, relate to the way in which we perceive that the natural world does have three dimensions, the information sources are usually referred to as "cues to depth", a term proposed by Woodworth (1938) that has no place in the Gibsonian approach. As will be seen later, one man's psychological invariant can be another's cue to depth.

In the context of the present work, one link between these two approaches stems from aerial (or atmospheric) perspective: the effect of atmospheric absorption and scatter that leads to a reduction in brightness and contrast with increasing distance from an observer. In the ecological framework, this gives rise to the invariants (in the Gibsonian use of the term) of brightness gradients and of contrast gradients, the cognitive approach holds that the brightness and contrast differences offer two cues to depth. The step from brightness gradients to brightness differences themselves being cues to depth has been made (Itlleson, 1960; Baird, 1992), but without offering a satisfactory explanation of why this should be so, and this will be discussed in Chapter 3. The step from contrast gradient to contrast difference as a depth cue has been justified (Ross, 1967, 1993; O'Shea, Blackburn and Ono, 1994).

A second link lies in the Ames Demonstration No.18 (Ames, 1949) which showed that increasing the luminance of an object would make it appear larger, or nearer to the
observer. Gibson (1950) was aware of such demonstrations, but doubted their relevance to the everyday world. Forty years ago, there were no simulators in existence using computer generated visual images; today, simulators with computer driven visual displays are used for a wide range of tasks. The flight simulator is perhaps the best known, while other uses include marine navigation training, passenger car development, tactical trainers for armoured vehicles, and most recently a simulator for those who will drive trains through the Channel Tunnel.

Simulator displays using computer generated images (CGI) are not presently able to reproduce optical arrays as complex as those of the natural world, though improvements in technology are continuously improving this situation. Most simulator displays can, however, produce unintended variations in luminance (and hence in brightness and contrast) which would not be offered by the natural world scene that the simulator seeks to depict. This work aims to establish the extent to which differences in luminance can influence judgements of the spatial layout of the simulator display, by considering the way in which brightness and contrast information can interact with the information from linear perspective.
1. General introduction.

This chapter is concerned with the first two experiments. The first was a pilot study, carried out to determine whether an informally observed effect would prove to be significant under the conditions of a formal experiment. The second set out to measure the magnitude of the effect. The effect in question is that of luminance differences, between the objects in a scene depicted on a simulator display, on their perceived relative position; the starting point is the view of Ames (1949) and Gibson (1950) that the brighter of two otherwise equal surfaces will appear to be nearer to the observer.

In the Ames Demonstrations (1949), Ames used two internally illuminated, and equally sized, balloons in a dark viewing chamber. If one balloon was made more luminant than the other, observers rated this balloon as nearer than the other, or larger than the other. Gibson (1950), referred to laboratory demonstrations of equally sized surfaces, but of different illuminance producing the same effect, but did not specify whether those surfaces were plane, or three dimensional. He subsequently included luminance gradients among his list of invariants in the natural world (Gibson, 1966).
Informal tests of the effect of luminance changes on perceived position were conducted with a scene that depicted three block objects - analogous to three bricks standing on end - standing in a line. The scene was generated on a BEST simulator (see Appendix 1), which rendered them in linear perspective, and showed the line at an angle to the virtual line of sight. Initially, each block was an equiluminant shade of grey, but the centre block could be made lighter or darker by selecting a different colour palette from the BEST control console. This change took only 15ms and was effectively instantaneous. To most observers, the change in brightness was accompanied by a shift in position as would be predicted by Ames (1949) or Gibson (1950).

Two points arose from this apparent shift in position. Firstly, this could have been an artifact of the BEST simulator system, arising from the switch between colour palettes, whereby the changed object actually changed position on screen. Although only a remote possibility, this point was addressed in Experiment 1 by using scenes obtained by video-filming real objects. Secondly, any change in object luminance would have also meant a change in object to background contrast. An alternative view to those of Ames (1949) and Gibson (1950) has been put forward by Ross (e.g. 1967, 1993), Farné (1977), and O’Shea, Blackburn and Ono (1994), to the effect that contrast changes, rather than luminance changes, moderate perceived depth and distance. These alternative views will be covered in greater detail in a subsequent chapter; for the first two experiments, the luminance hypothesis formed the starting point.
2. EXPERIMENT 1

2.1 Introduction.

It was shown in Section 1 that there is some evidence suggesting that the 'brighter' of two objects or surfaces will be perceived as being nearer to the observer, or as being larger, or both. These reports generally relate to studies in which the size and luminance, or size and illuminance of the objects or surfaces are the only variables in the information available to the observer (e.g. Ames, 1949). Such studies that have used stimuli displayed on a monitor screen, have tended to use that screen as a flat surface and not taken advantage of the potential to display scenes that contain such other depth information as linear perspective or occlusion - such as would be the case if the monitor screen was the display device for a 3-D simulator. If the screen is used to present 3-D information, then it becomes a transparent surface. This term was used by Pirenne (1970) to refer to a transparent Leonardo window intersecting the cone of vision. The observer is aware of the surface, but can see through it to the scene beyond.

However, comparisons with a Leonardo window are not wholly appropriate. Pirenne (1970) wrote in relation to paintings or photographs which generally only depict, rather than simulate, a natural world scene. The distinction between depiction and simulation can, on occasion, be a very fine one. A painting or photograph depicting a portion of the natural world may also, under certain conditions, simulate the natural world structure of the light reaching the observer. A simulator will not usually (see Chapter 2) reproduce the natural world light structure of the depicted scene, but an observer is intended to respond as if it did. Modern dictionary definitions of 'simulation' tend to
focus on the training function, so that the distinctions between depiction and simulation become those of intent and action.

In many simulators the screen surface forms part of the simulation and represents an actual window (e.g. an aircraft windshield, or a tank driver's periscope). Such actual windows in simulator displays are normally viewed with both eyes, and that practice will be followed here. Many of the Ames Demonstrations were set up for monocular vision, and some of the effects were reduced when the stimulus was viewed with both eyes (see Ittleson, 1960, for a detailed account); thus, with binocular vision, very weak effects would not be expected to attain significance.

Informal trials using the BEST simulator to generate an image containing a depiction of identical objects and then changing the luminance of one of them, had indicated that the object so changed would appear to change position. From this informal observation, generalised across six observers, it was assumed that an array of equally sized and equally spaced objects, varying in luminance, would appear to have an unequal spacing between the objects, unless the effect was due solely to the change itself.

The first aim of this experiment was to determine if the effect of differences in object luminance on perception of relative object distance, that had been noted on an informal basis on a simulator monitor, would obtain under experimental conditions. A second
aim was to develop a methodology that could be used for further studies, if the effect of object luminance proved to be significant, and the third aim was to establish whether the effect was an artifact of the computer image generation, or would be present on any monitor screen.

**Basis for the experiment.**

Observers were shown a set of scenes which varied in the luminance ordering of the objects in them, and were required to make a forced choice decision on the position of the centre object in the display relative to the other two objects. To this end, a video film was made by recording a set of three blocks identical in size, shape and orientation, and painted in three shades of grey to give three different luminance values. The blocks were arranged in line, equally spaced, and at varying angles and distances, the order of their luminance being manipulated in the expectation that one ordering would produce a greater apparent displacement than the alternative.

Figure 1.1 is typical of the stimuli used, while Figure 1.2 indicates a possible effect of the luminance variations. Following Ames (1949), if a brighter object is perceived as being either nearer or larger, and the darkest object is in the centre of the line, then the centre object should be perceived as being nearer to the rear object, with the strongest effect being obtained when the brightest object is in front.
Figure 1.1: Typical stimulus as seen by subject.
If Brighter is perceived as Nearer, or Larger:

a) Effect should be strongest when brightest object is nearest.

hence:

b) Middle object should appear further back when front object

is brightest.

Figure 1.2: Possible effect of luminance differences.
2.2. Method.

Subjects.
These were 20 first-year Psychology students, 16 female and 4 male. All were volunteers, and were naive to the purpose of the experiment.

Equipment.

The stimuli.
These scenes were generated by taking video-film of a set of three blocks. These were of uniform size, dimensions 42 mm high, 17 mm wide, 12 mm deep, painted light, medium and dark grey, using a matt paint. Each scene was created on a worktable of a size that took its perimeter beyond the focus range and visual angle of the video equipment. The ground plane was a sheet of 1 mm graph paper which, together with a template, permitted accurate positioning of the blocks. A tracing paper overlay covered the graph paper so that the texture effect of the graph paper grid was eliminated. The scene was illuminated by three Quartzcolor Redhead 800watt lights using their spot setting. They were positioned to the sides and above the scene, so that no block cast a shadow on another, and producing multiple soft shadows on the background that offered no clear positional information. The background was also of tracing paper. When displayed on a video monitor which had previously been set for brightness and contrast with a standard tuning signal, this gave the following luminance values:
Light Grey  
Medium Grey  
Dark Grey  
Background (blue-grey)  

A National Panasonic CTVC WV3300B video-camera with the standard lens replaced with a Modelscope (Specfield Ltd, No. 2253) - an endoscope with angled end mirror - originally designed to produce true linear perspective when used with architectural models, was mounted on a heavy tripod with horizontal (y-axis) adjustment in addition to vertical movement. This enabled the optical centre of the Modelscope to be positioned 5 mm above the ground plane and at a precise distance from the blocks. The camera output was fed to a JVC Umatic CR8200E recorder, with RM88V remote controller. The master tape was recorded on 'Insert Mode' in order to provide a synchronisation and timing signal to assist with subsequent editing.

The blocks were in a line, with the centre object positioned on the Modelscope axis of view, at three distances (200, 250, 300 mm) and at four angles (20, 30, 40 and 50 degrees). Two sets, each of 24 views were recorded, the first set had the blocks equally spaced (40 mm centres), while for the second set, the centre block was moved forward by 10 mm. The purpose of this large displacement was to provide views in which the spacing was visibly not equal, with the intention of reducing the possibility of subjects forming an assessment of the experimental design. The angle to the axis of view was from right or left, all views from the right having the light grey block nearest the
viewpoint, all views from the left having the medium grey block nearest. The dark grey block was always in the middle of the line. Thus, two luminance orderings were used here: Light-Dark-Medium (L-D-M) and Medium-Dark-Light (M-D-L).

The views were edited into a presentation tape. This took the form of a practice sequence (using views taken from a different viewing height) and four test sequences of twelve views. Each sequence was balanced for Right and Left viewpoints, and for object spacing. The viewing angle and distance factors were pseudo-randomised to give an equal distribution across the four sequences. Each view (preceded by a 3 second red warning screen), was presented for 10 seconds, followed by a 3 second black screen (timings accurate to +/- 0.12 seconds).

**Presentation equipment.**

The Umatic recorder and controller were used to drive a Sony Trinitron 21" video monitor. Subjects were positioned centrally in front of the monitor, and 1.8 metres from it (this distance affording the same visual angle as the normal viewing distance and screen size of the BEST simulator). They were seated at a table, thus constraining their position but without a fixed head position. The room used for presentation had indirect lighting, permitting a low level of ambient light (0.7-0.8 lux) without any reflections on the monitor screen.
Procedure.

On being seated, subjects were given a printed set of instructions, a perspective drawing of a typical scene, and a response sheet. For each view, they were required to judge whether the centre block was central between the other two, nearer to the front block, or nearer to the back block. The response sheet had a set of three boxes for each view, labelled 'Front' 'Central' 'Rear', arranged so that the 'Front' box was nearest to the subject, and subjects were told to mark the appropriate box in any manner they wished. During this period the tape was paused on a title screen. The practice series of views was presented, the tape paused, and subjects were asked if they had any problems with the task. The experimental series were then shown, with a 30 second pause between series.

Design.

This was a simple within subjects design, each subject making one judgement per view. Thus: twenty subjects each made one judgement for each of three distances x four angles x two luminance orderings.

2.3. Results.

For analysis, each judgement was turned into an error score: a judgement of 'Central' being scored 0, 'nearer the Front' and 'nearer the Back' being scored -1 and +1
respectively. When summed across angles, this gave a potential range from -12 to +12 for each luminance order. It was expected that the judgements for the unequally spaced views would be correct and effectively this was the case; with the scores in each condition exceeding -11.7, these views were discarded prior to analysis.

Mean across subject error scores for the two conditions were:

<table>
<thead>
<tr>
<th>Medium-Dark-Light</th>
<th>Light-Dark-Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean 3.20</td>
<td>mean 7.10</td>
</tr>
<tr>
<td>S.D 3.14</td>
<td>S.D. 2.75</td>
</tr>
</tbody>
</table>

and a paired t-test between the two conditions gave:

Mean difference 3.9; S.D. =3.478; d.f. =19; t=5.02; p < .001.

Both the mean error scores are positive, indicating an apparent rearward shift of the dark centre object relative to the lighter front and rear objects.

2.4. Discussion.

The results indicate a highly significant effect attributable to the variations in object luminance ordering.

These results can not be taken as direct confirmation of those effects noted by Ames (1949), since Ames used only two objects, and started from a position of equal luminance and equal angular extent, but they do show a similar effect. It is possible that had a control condition, where all objects were of equal luminance, been used, that some
judgements would still have put the centre object nearer to the rear one. Such a
collection would have required that judgements be made on the basis of linear perspective
alone, and the two conditions where the objects were of differing luminance would have
increased the amount of information available. The two conditions used here enable a
direct comparison between the two luminance orderings.

The studies of Ross (1993), or O'Shea et al (1994), would have predicted a forward shift
in the perceived position of the centre object, given that all objects were darker than the
background. Since this did not occur, it may be concluded that the information from
linear perspective specified the basic scene layout, and that this was then moderated by
the luminance information rather than that from contrast.

The results do suggest that differences in object luminance will alter subjects’ perception
of their relative distance. If this is assumed to stem simply from a ‘Brighter = Nearer’
effect, then each of the luminance orderings could be expected to result in the Light and
Medium shaded objects being perceived as relatively nearer to the observer than the
Dark object. On the basis of the error scores this did occur, and as can be seen above,
the luminance order L-D-M produces a much stronger effect than the order M-D-L. The
results also indicate that the effect is not confined to images generated by computer.
2.5 Conclusion.

An effect of luminance variations on observers' judgements on the relative positions of the objects displayed has been shown. However, given only frequency counts as raw data, no estimation of the magnitude of the effect is possible. Measurements of the size of the effect are the objective of the next experiment.
3. EXPERIMENT 2.

3.1. Introduction.

Experiment 1 showed that variations in the luminance of objects in a scene lead to differences in their perceived position; Experiment 2 was planned to investigate the magnitude of the effect. The range of luminance variations was increased to include ordinal luminance and contrast gradients, as being more characteristic of the natural world. Luminance gradients are seen as offering a cue to depth by Ittleson (1960) and Gibson (1966). Contrast gradients are seen as a cue to depth by Farne (1977) Ross (1993) and O'Shea, Blackburn and Ono (1994). The two cues of luminance gradient and contrast gradient may coincide, or may oppose one another. Each can be caused by atmospheric absorption, and may vary with the amount of water vapour or dust in the air.

Rather than video-filming real objects, the scenes were generated on the BEST Simulator and transferred to tape using the direct PAL video output from the BEST. By directly translating the pilot study scene dimensions into BEST ‘units’ , a direct comparison between the two methods of scene generation was enabled, and it was assumed that the luminance manipulations would produce a similar effect to, and in the same direction as, the pilot study: the ‘brighter object being seen as nearer’ of Ames (1949), rather than the ‘higher contrast being seen as nearer’ of O’Shea et al (1994). In order to get a more direct measure of the strength of any effect of the luminance differences, a method of
adjustment replaced the method of asking subjects to make categorical judgements. The stimuli scenes contained the same potential depth information of relative brightness, simple linear perspective and relative size as in the pilot study.

If it is assumed that the observer to object distance will appear to vary with the luminance of an object, and that an increase in luminance will result in that object appearing to be nearer - proportionate in some way to the luminance difference, then a line of objects of differing luminance could potentially appear to have its linearity altered, or its angle to the line of sight, or both. Two such possible angular shifts are shown in Figure 1.3. If contrast, rather than luminance, affects the apparent position of the objects in a scene, then the angular shift would be in the opposite direction.

The first aim of this experiment was to determine if similar stimuli with the same luminance differences as used in the previous study, would produce a similar effect when the stimulus images were computer generated, and to obtain some measure of the effect for different orderings of object luminance. On the basis of Experiment 1, it was expected that the luminance ordering Light-Dark-Medium would lead to a greater apparent shift of the centre object toward the rear than would the ordering Medium-Dark-Light; a prediction based on contrast varying inversely with distance, and a background of higher luminance than any object in the scene would, following O'Shea et al (1994), have the centre object shifted forward.
Figure 1.3: Possible effect of luminance on angle.
Where the ordinal luminance orderings are concerned, prediction of any outcome is more complicated. The luminance order Light-Medium-Dark (matching the natural world negative luminance gradient) could support the information from perspective, as could the order Dark-Medium-Light (following the natural world negative contrast gradient). In either event, the effect of the reverse condition would be to compress the perceived length of the line. Any apparent shift in the relative position of the three objects could be based on their differing luminance or contrast, with or without the background being involved, or by taking combination of luminance and contrast into account.

A second aim was to determine if monotonic luminance orderings would affect the perceived angle of the line of objects. Following Figure 1.2, one could expect the luminance ordering Dark-Medium-Light to produce a greater apparent shift toward the normal than the order Light-Medium-Dark.

Scenes depicting the line of objects, with four luminance orderings were presented on the display monitor of the BEST simulator. The line was shown at three different angles to the line of view. Subjects were required to adjust a mechanical device, carrying three blocks, to match the scene depicted on the monitor.
3.2. Method.

Subjects.

Ten subjects - 7 female, 3 male, with an age range from 20 to 38 years - took part in this experiment. They were either undergraduate or post-graduate psychology students at the University of Surrey.

Equipment.

The stimuli.

The BEST was programmed to replicate the stimuli scenes used in the pilot study, by translating directly from millimetres to BEST 'units'. Thus, each scene contained three block objects, 42 units high, 17 units wide and 12 units deep, equally spaced with 40 units between the centres of the object bases, in a straight line such that the depth dimension was parallel to the line, and the line passed through the centre of the width dimension. The eye position (theoretical point of view) was positioned 5 units above the baseline at a radius of 250 units from the centre of the centre object. Viewing angles of 25, 40 and 55 degrees were used, defined as the included angle between the line of objects, and the virtual line of view through the centre object. Thus, the 25 degree viewing angle has the line of objects rotated 25 degrees from the line of view. Typical scenes and scene layouts are shown in Figure 1.4.
All stimulus sets are shown in plan view

Order 1  Order 2  Order 3  Order 4

a) The four object luminance orders.

25 Deg.  40 Deg.  55 Deg.

b) The three angles of the line of objects.
Line angled to right (25 deg shown) or left (40 & 55 deg shown)

Figure 1.4: Stimulus layouts for Experiment 2.
In each scene the front face of each object was shaded to appear as light, medium or dark grey, with the side faces then being shaded slightly lighter than the front faces. This gave an illusion of object solidity similar to that of the video-filmed stimuli; the computer generated scenes did not have the multiple shadows of that stimuli set.

The objects were arranged so that the shading followed one of four orderings (defined from the front of the line):

- Mixed - light first: Light, Dark, Medium
- Mixed - dark first: Medium, Dark, Light
- Ordinal - light first: Light, Medium, Dark
- Ordinal - dark first: Dark, Medium, Light

The luminance values were set by measuring with a Minolta Croma-meter on the Sony Trinitron video monitor, driven by a PAL video output on the BEST.

These values were:

- Dark Grey: 17 cd/m²
- Medium Grey: 33 cd/m²
- Light Grey: 78 cd/m²
- Background (blue-grey): 145 cd/m²

It was not possible to match the luminance values of the pilot study exactly, due to the response of the Trinitron to increments in the BEST colour lookup table.

The video-tape was edited so that for each luminance order and viewing angle, ten presentations were made of each scene. For each angle, presentations were made equally to the right and left of the axis of vision. The order of presentation was pseudo-randomised: the four luminance orders, three angles and two directions of angle being randomly placed into a 24-scene sequence, which was then repeated five times; eight additional scenes using a 90 degree viewing angle were incorporated (as distracter views) at random into the complete sequence, which was then broken down into four series of
32 scenes presentation. Each scene was presented for seven seconds, preceded by a three second warning flash and followed by three seconds of black screen. A six scene practice series was then placed at the start of the tape.

The adjustment device.

This was constructed as a means of obtaining subjects' responses. Illustrated in Plate 1, it consisted of three blocks, 42 mm x 17 mm x 12 mm, arranged in a line 80 mm from centre to centre of the end block, with the centre block free to slide between the other two, with the assembly mounted on a turntable. Two scales, not visible to the subject, gave the position of the centre object relative to its central position, and of the rotation of the turntable.
PLATE 1: THE ADJUSTMENT DEVICE

Top: As seen by the subject.
Bottom: Showing the scales for rotation, and for lateral movement of the centre block.
Presentation equipment.

The same equipment (JVC CR6650E U-matic Video-recorder with JVC RM-70U remote control box, and 19" Sony Trinitron monitor), and experimental setup referred to in the pilot study were used.

Procedure.

Subjects were seated centrally in front of the monitor at a distance of 1.8 metres - giving the same visual angle as the smaller BEST monitor, and sufficiently far that the pattern of individual pixels was not discernable - with a chinrest being used to maintain head location. The adjustment device was positioned along, but just below, the line of sight, at a distance of 450 mm. They were each given a printed set of instructions which described the nature of the scenes, and required them to adjust the device - both in rotation, and by moving the centre object - so as to match as closely as possible the scene presented on the monitor. They were told that they could start the adjustment as soon as the scene appeared, and would be given unlimited time to complete the adjustment after the seven second presentation period. This was enabled by stopping the video-tape during the black period following each scene. This pause in turn enabled the recording of the readings from the device. After each presentation, both adjustments were moved to positions that required them to be remade for the next presentation.
**Design.**

A within subjects design was used. The independent variables being the ordering of the objects in terms of their luminance, and the angle of view; and the dependent variables being the measurements of position (from a central zero) and of angle obtained for each scene. Each subject made 10 judgements for each of the 4 luminance orders and 3 view angles for object position and angle of presentation.

**3.3. Results.**

For each subject, a mean score across the ten readings for each luminance order and angle of the line of objects was calculated. Since there are two dependent variables for each combination of luminance ordering and angle of the line of objects, these will be treated separately.

**Judgment of position or relative distance.**

The means across subjects for each combination of luminance order and angle are as shown in Table 1.1.
Table 1.1 Rearward displacements of the adjustable block.

<table>
<thead>
<tr>
<th>REARWARD DISPLACEMENT FROM CENTRE (mm)</th>
<th>ANGLE OF OBJECT LINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>LUMINANCE ORDER</td>
<td>25°</td>
</tr>
<tr>
<td>LIGHT-DARK-MEDIUM</td>
<td>0.84</td>
</tr>
<tr>
<td>MEDIUM-DARK-LIGHT</td>
<td>-0.20</td>
</tr>
<tr>
<td>LIGHT-MEDIUM-DARK</td>
<td>0.49</td>
</tr>
<tr>
<td>DARK-MEDIUM-LIGHT</td>
<td>0.16</td>
</tr>
<tr>
<td>MEAN</td>
<td>0.32</td>
</tr>
</tbody>
</table>

It will be seen in Table 1.1 that - with the exception of the Medium-Dark-Light ordering at the 25° angle of view - all the mean scores are positive; this indicates that the mean position of the centre object is seen as shifted toward the rear of the line: the predicted direction.

Analysis of Variance on the factors of luminance Order and angle of view showed both main effects to be significant:

- Luminance Order d.f. = 3, 24 F = 11.3 p = 0.001
- Angle of View d.f. = 2, 16 F = 4.25 p = 0.015

but the interaction between them was not (p = 0.45).

The predominantly rearward shift suggests an effect due to luminance rather than to contrast, in that the perceived shifts are greater when the front object has the highest luminance value (see section 3.1 above). Since the adjustment device permitted only
movement of the centre block, these scores can only represent subjects’ perceptions of
the position of the centre object relative to the others, and not their percepts of the
overall length of the line of objects.

The overall means show that Order 3 (Light-Medium-Dark), analogous to the natural
world luminance gradient of Gibson (1966), shows the greatest rearward displacement;
Order 4 (Dark-Medium-Light), analogous to the daytime natural world contrast gradient
due to atmospheric perspective, shows the smallest rearward displacement. This
suggests that the negative luminance gradient may have differentially increased the
interobject spacing specified by perspective.

Judgment of angle.

The means across subjects for each combination of luminance order and angle are shown
in Table 1.2
### Table 1.2. Angular errors in setting the adjustment device.

<table>
<thead>
<tr>
<th>LUMINANCE ORDER</th>
<th>ANGLE OF OBJECT LINE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25°</td>
</tr>
<tr>
<td>LIGHT-DARK-MEDIUM</td>
<td>0.67</td>
</tr>
<tr>
<td>MEDIUM-DARK-LIGHT</td>
<td>2.38</td>
</tr>
<tr>
<td>LIGHT-MEDIUM-DARK</td>
<td>3.36</td>
</tr>
<tr>
<td>DARK-MEDIUM-LIGHT</td>
<td>2.96</td>
</tr>
<tr>
<td>MEAN</td>
<td>2.45</td>
</tr>
</tbody>
</table>

All the mean values are positive, indicating that in every case the angle is seen as being nearer to the normal than its simulator definition. However, analysis of variance on the data for angular shift, on the factors of luminance order and angle of view, does not show any significant effects for either of the Within Subjects Effects:

- **Order**: d.f. = 3, 24 F = 2.07 p = 0.131
- **Angle**: d.f. = 2, 16 F = 2.07 p = 0.08

The interaction was also not significant (p > .8).

### 3.4. Discussion.

It can be seen that from these results that the manipulations of object luminance have had a highly significant effect on perceptions of the relative position of the objects, and that the angle of view also has a significant effect. Neither of the manipulations has had a significant effect on judgments of the angle of the line of objects to the line of view, although the effect for angle of view approaches significance.
Judgements of relative position.

The variations in luminance between objects have had a significant effect on the subjects’ perception of their relative positions with this particular experimental setup. The equipment was not designed to measure any effects on perceptions of the overall length of the line of objects, whether from the luminance variations or from perspective.

Thus far, reference has been made to 'luminance variations' as opposed to 'contrast'. Each of the objects is of different luminance to the background, and thus a foreground to background contrast can be determined. But each object also differs from the others. In the views at 25 degrees, each object partially occludes the one behind, thus there is contrast between contiguous object surfaces as well as between object and background. In the views at other angles, a clear separation exists between objects which is filled by the screen background. The luminance and contrast gradients across the scene objects, irrespective of slope, have therefore been of two different degrees of complexity (see Figure 1.5).

The two ordinal luminance orders used here (orders 3 and 4) had the luminance and contrast gradients opposed to each other, due to the background luminance being higher than any of the foreground objects. It would seem that in this experiment, the condition with the negative luminance gradient (order 3) has had a greater influence on judgements of relative position than has the condition with the negative contrast gradient (order 4).
These diagrams indicate changes in complexity in the luminance values across the screen horizontal centreline.

Figure 1.5 Changes in screen luminance.
Judgements of angle.

It can be seen from the across-subject means in Table 3.2 that all the angles are seen as nearer to the normal as found by Tausch (1954), and Wade (1982), but that neither the main effects, or their interaction, reach significance when only the angular data are considered. One reason for this may be the partial occlusion of the centre and rear objects, referred to above and shown in Figure 1.5, creating visual arrays of differing complexity.

A second reason may be that the objects did not appear to be in a straight line. Six of the ten subjects reported that the centre object was often seen as "being out of line" or that the objects were not seen as "being in a straight line". This would be the case if the perception of their relative positions was being influenced directly along the line of view, as well as along the line on which the objects were located. Since the virtual line of sight runs through the centre object, which in turn is central on the screen, the argument that contrast varies inversely with distance (Ross, 1993; O'Shea et al, 1993) would suggest that for orders 1 and 2, the centre object was perceived as out of line toward the observer. Following the approach that luminance co-varies with distance would lead to perceptions of the ends of the line, rather than the centre moving near to the observer for orders 1 and 2.

If the position of any object was judged as other than the correct value, this would require observers to form an approximation of the angle of line of objects, and then try
to match this new line with the adjustment device. Gregory (1970) referred to the visual system as having to weight conflicting information in order to arrive at an acceptable percept. It seems possible that to match the influence of either luminance, or contrast, could require more adjustments than were available to the subjects.

3.5. Conclusion.

It has been confirmed that luminance differences have an effect on perception of the relative position of the objects in a scene displayed on a monitor. However, the potential for any or all of the objects to appear to shift position does preclude establishing a fixed reference point from which absolute shifts can be measured or calculated.

4. An Overall Assessment.

It has been demonstrated that luminance differences can moderate perspective information where a scene is presented on a monitor screen. The next chapter will consider the way in which computer generated images have come to be the norm for simulator displays, and the perceptual problems involved. However, the results of the two experiments here have no firm theoretical base, and could be considered as an electronic extension of the Ames Demonstration 18: Chapter 3 will seek to establish a basis for the effects observed.
CHAPTER 2: SIMULATORS.

1. Introduction.

Each of the two experiments reported in Chapter 1 has indicated that where an image displayed on a Cathode Ray Tube (CRT) represents a scene in three dimensions, luminance differences between objects in the scene can affect perceptions of the spatial layout of that scene. In Experiment 1, the image was a video recording of a real group of objects, presented on a video monitor; Experiment 2 used a computer generated image (CGI) presented on the display monitor of a BEST simulator. These are the two main methods of image creation used on 3-D pictorial simulators, with CGI having been the predominant technique for the last two decades (see IEE 266, 1983; IEE 267, 1986; Harris, 1984). This chapter will outline the history of simulators, the manner in which the displayed images are produced, and compare the natural world information that specifies a scene in depth with that of the simulator display. Some of the limitations of CGI and CRT display will then be discussed.

2. A brief history.

It is easy to regard the simulator as a product of the electronic age, yet simulators have been with us from, at least, the middle ages. The quintain, a target mounted on a horizontally revolving beam, provided a combat simulator for mounted knights equipped with lances. The penalty for error was far less than for the real situation, and thus the simulator can be seen as a device to enable training to take place at reduced cost.
The first real flight simulator, the Link Trainer of the 1920’s, offered pilots a method of obtaining some knowledge of instrument flying skills without the risk of damage to real aircraft. The Link Trainer continued in use into the 1950’s, when its electro-mechanical technology was joined to the emerging video technology to provide the direct forerunner of the modern computerised simulator. In the age of the Link, it was not possible to provide any credible visual display of the world outside the simulated cockpit, rather a black fabric cover was drawn over the cockpit as would be the case when the trainee passed on to training in real aircraft. The cockpit was mounted in such a way as to provide limited motion in yaw, pitch and roll, and provided with a realistic set of instruments. Control movement led to cockpit movement with matching instrumentation movement. There were no problems of visual perception with the Link, although instrument faults could still limit the simulation of reality.

The advent of video technology enabled the concept of the Link to be taken through to the point at which a visual display simulated a world outside the cockpit. A model terrain was laid out on the floor of the simulator building, and a video camera took a flight-path over this model as dictated by the movements of the cockpit flight controls. The video picture was displayed to the pilot in what would normally be the plane of his windscreen. The display provided what was, in many ways, a perceptually good simulation, but had some very real limitations. Flights were limited to the bounds of the model, the degree of detail was a function of the scale of the model, and the size of the model terrain was limited by the building that housed it. A further limitation was that the camera line of sight could not be brought down to the ground plane: even twenty
years later, using an optical device developed for architects (the ModelScope), it was not practical to simulate a takeoff or landing. Simulator flights commenced and terminated between 5 and 10 metres above ground. The camera/modelboard still has a role to play: the space limitation has to some extent been overcome by mounting the board vertically, and it can still be the simulator of choice where a high degree of detail and a relatively small terrain area are required, as, for example, in training pilots in ground attack skills.

The use of computers to generate images for use in a simulator system has grown at an exponential rate. In essence, a satisfactory image generation system must be able to take a database of all the components in a virtual world, to calculate the appearance of those of them which will be in view from a given station-point at any given time, and to generate the image on the display screen at a rate sufficiently fast to provide a smooth animation to the image. If these requirements are met, the electronic image can satisfy the visual needs of a simulator that would, for example, allow for a nonstop round the world flight, something that would be inconceivable with a camera/modelboard setup. As will be seen later, the computer generated image has considerable limitations, some of which are being reduced with the continuous improvements in display technology, and some of which are cut down with each improvement in processor and memory chips. As computers have become both far less costly, and more powerful, their use in the field of simulation has been extended to more mundane forms of transport. The marine navigation simulator is far removed, in terms of speed, from the world of fast jet aircraft. This, for example, allows training in the pilotage skills required to navigate into a strange harbour at simulated speeds of say 5 to 20 knots. Simulators are now
Another growth area is that of interactive or networked simulation, such as would enable a group of armoured vehicles to conduct manoeuvres on the same virtual terrain at the same time. As will be seen later, the work to be described is of more relevance to those simulators where slower travel speeds are the norm.

3. Producing the display.

What the computer does is to take the set of data defining a virtual landscape (or seascape), compute a description of that part of the landscape that can be seen from a specified viewpoint, and pass this description to a graphics processor that generates the display on the monitor. When input is received from a simulator control this process must be repeated, and if smooth animation is to be achieved, the monitor screen must be redrawn faster than 60 times per second.

As an example, consider a simple scene that can be said to represent a three-dimensioned virtual world: two cubes of identical size, standing on a ground plane with a background. All simulator scenes using CGI are assembled from a number of polygons, some in isolation and others grouped to form a 3-D object. First the ground plane has to be defined in terms of the Cartesian coordinates of its apices. Next, the background must be similarly defined. After this, the first cube can be defined: of its six faces (polygons), one is coincident with the ground plane and can be ignored hereafter. The faces are defined by specifying the apices that contain each face. The second cube can
be created by copying the first to a different location. This creates an electronic
analogue of a wire frame model. Now, the colours that will be used to paint each face
can be defined; this is done by specifying the proportions of Red, Blue and Green to be
used. Finally an eye position and a line of sight are determined. Assume that this is
25% of the height of a cube above the ground plane. Further assume that the two cubes
are disposed at equal distances to the right and left of the line of sight, but that one is
10% further away from the eye position.

The process starts by calculating the height of each vertical edge, and then the length of
the lines joining the verticals. After this, further calculation eliminates those faces that
are not visible from the eye position. The analogue becomes that of the perspective
drawing. This, together with the face colour information is now passed to the graphics
processor which now produces the information to be sent to the monitor, to produce the
appropriate display. The screen displays four objects: on the specification above, two
of them will not be cubes but will be the two faces from each cube that can be seen from
the station-point. The other two will be the ground plane and background with the
boundary between them forming a horizon line. Now move the station-point - the eye
position - a trifle nearer to the two cubes. This will require some form of input to the
computer, but the nature of this input does not matter at this stage. The calculations
must be redone from the beginning, and a complete new picture sent to the screen.
Next to be considered is the monitor. The picture does not appear instantaneously, it is built up in a progressive manner. Inside the CRT, three beams of electrons (representing the Red, Blue and Green (RGB) values), focused to coincide just behind the face of the screen, trace a line horizontally across it. As they do so, they pass through a perforated metal plate known as the shadow mask and strike tiny dots of phosphor compounds (RGB again) which fluoresce, the fluorescence fusing to produce a small spot (pixel) of colour. After each line (the Raster line) is painted, the beams fly back to a point just below the start of the line just painted and start to paint a new line. This process continues until a complete screen has been painted. Since the fluorescence decays rapidly after the beams have passed, the screen must be repainted (refreshed) before the picture starts to fade, and preferably faster than the human visual system can detect.

Refreshing the screen is simple for a static scene, but animating the picture poses several restrictions. The computer must complete all the computations for each picture before it can pass the results to the graphics processor, and this in turn must also create a complete picture. Current practice is to have a number of storage buffers (framestores) each holding the details for one picture (frame). A typical setup would have one framestore holding the details for the frame currently displayed, a second holding the details for the next frame, and a third being filled as the details for the following frame are computed. Thus, apart from the need to refresh the screen sufficiently fast, it must also be updated for absolute changes in the picture presented.
At this point, the first real limitation becomes apparent: each of the computations takes a finite period of time, so that real-time animation cannot be effected unless all computations for a frame are completed by the time that the preceding frame is called for. Although a faster processor and more memory will help, there is always a very real limit to the number of polygons that can be displayed in any one frame. In practical terms this means that the programmer has to choose between detail in the virtual scene and the area which that scene is intended to represent. Regardless of the choice, the scene presented will be sparse in detail compared to even a video-film of the natural world terrain. This lack of detail has the effect of emphasising those cues which enable the observer to make sense of the scene, and in particular the sense intended by the designer / programmer.

4. Presenting the display

Two limitations reside in the monitor itself. Firstly the monitor can be of interlaced or non-interlaced type. It has already been said that the picture is built up from lines of pixels. An interlaced monitor does not present the complete picture at one pass. First the even numbered lines are painted, followed by the odd lines. This requires two further framestores - one for each half frame (or "field") in the current picture - but this complication is balanced by the fact that each half frame only has to be computed at half the speed. This type of display can cause perceptual problems, both in regard to an apparent flicker, and that the second limitation, or rather a technique for minimising one of its effects, can give rise to apparent motion from the half frames where no motion was intended.
The second limitation is that of screen resolution. The lines of pixels mean that the screen is essentially a matrix of cells, each of which can have only one colour. The picture displayed is in effect a form of electronic pointillism. The monitor on the BEST Simulator used for this research can display 570 pixels on each of 512 lines, which gives a total of 219840 pixels. This may seem a large number, but is rather less than the number of blades of grass in one square metre of average lawn. It is not therefore practical to provide any texture, in the conventional sense of the term.

Moreover, since each pixel is rectangular in shape (proportional to the pixel x line count), and every edge must be built up from a series of pixels, any diagonal edge will have a series of steps (the staircase effect) normally known as aliasing. It is the staircase effect, linked to the alternate lines of an interlaced monitor, that can give rise to apparent motion. Aliasing can be dealt with in software (making more demands on processor power and memory) using any one of a number of algorithms which effectively blur the steps, and make them appear smaller than they are in reality. What none of these algorithms can do is allow any defined polygon in the scene to be scaled in units of less than one pixel. This places a finite limit on the absolute virtual distance over which reasonably accurate scaling can take place. The displayed scene is not only sparse with regard to the population of polygons within it, it is also crude in the sense that objects (as defined by their edges) cannot be drawn with real precision. The Rediffision Evans and Sutherland SP2 flight simulator of 1978 could only display 512 edges (Taylor, 1983), generally limiting its use to night landing training. Stenger et al (1981) contrasted 5,000 edges in the best CGI of that time with the figure of 100,000
edges average in an (American) television picture, and it is the current convention to talk in terms of polygon counts per square kilometre of depicted scene, and of pixel counts per degree of visual angle, when discussing specific representational requirements (Padmos and Milders, 1992b). The key requirement is that the scene portrayed is sufficiently realistic to enable training to take place, and hence that such depth cues as are present should not lead to inappropriate percepts of the relative positions of objects in the scene.

5. Depth perception and the cues to depth.

In viewing the real world there are multiple sources of information potentially available to the visual system to specify depth and spatial lay-out; these so called ‘cues to depth’ (see, for example, Schiff, 1980, Harker and Jones, 1980) are summarised in the first column of the table below (adapted from Hone and Davies, 1993). They are grouped into the physiological cues, such as stereopsis, and eye vergence; the pictorial cues, so termed because they can be incorporated into pictures on a flat surface, such as linear perspective and texture gradients; the motion-based cues which arise either from observer motion or from object motion; and the ‘brightness’ cues. These cues differ one from another in their reliability and in their resolution; some, such as stereopsis, offer fine grained information for relative depth, but only at short absolute distances, whilst others, such as occlusions within the retinal image, offer coarse grained information of only partial reliability, but can function over a much greater absolute distance. Nevertheless, they are all cues to depth, since to varying degrees they co-vary with distance; and they offer sufficient information for reliable distance perception as they all normally converge on a common solution to the assessment of relative distance.
During the renaissance, painters such as Leonardo discovered that the pictorial cues could be incorporated into paintings to produce illusions of depth and space; pigment on a canvas could so structure the light reflected from it, that an eye placed at the station-point (or the point of construction), would receive the same kind of information as would have come from the depicted scene, Pirenne (1970), Kennedy (1974), and many others. However, a major limit on the power of these illusions is that whilst the pictorial cues are specifying a scene in depth, the biological and motion cues are specifying a plane surface that is approximately at right angles to the line of sight.

This cue conflict reduces the effectiveness of the illusion: the perception of depth is less compelling than when these conflicts are reduced by monocular viewing through an aperture which removes stereoscopic and motion parallax information. Even the presence of a frame around the picture can strengthen the perception of flatness: this is true for both CGI (Stenger et al, 1981), and if the natural world is viewed through a frame (Eby and Braunstein, 1993). In some situations where an observer would expect to see a frame, say a tank commander looking through a periscope, the conflict disappears; but to simulate that same commander with his head out of the turret would require a projection display if the conflict is to be avoided.
Table 2.1. Depth cues and their potential for conflict on the monitor.

<table>
<thead>
<tr>
<th>REAL WORLD CUES</th>
<th>POTENTIAL FOR CONFLICT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHYSIOLOGICAL</td>
<td></td>
</tr>
<tr>
<td>STEREOPSIS</td>
<td>YES</td>
</tr>
<tr>
<td>CONVERGENCE</td>
<td>YES</td>
</tr>
<tr>
<td>ACCOMMODATION</td>
<td>YES</td>
</tr>
<tr>
<td>PICTORIAL</td>
<td></td>
</tr>
<tr>
<td>OCCLUSION</td>
<td>NO</td>
</tr>
<tr>
<td>HEIGHT IN VISUAL FIELD</td>
<td>NO</td>
</tr>
<tr>
<td>LINEAR PERSPECTIVE</td>
<td>NO</td>
</tr>
<tr>
<td>TEXTURE GRADIENTS</td>
<td>NO</td>
</tr>
<tr>
<td>MOTION</td>
<td></td>
</tr>
<tr>
<td>OBSERVER MOTION</td>
<td>YES</td>
</tr>
<tr>
<td>OBJECT MOTION</td>
<td>NO</td>
</tr>
<tr>
<td>&quot;BRIGHTNESS&quot;</td>
<td></td>
</tr>
<tr>
<td>CONTRAST GRADIENTS</td>
<td>YES</td>
</tr>
<tr>
<td>LUMINANCE GRADIENTS</td>
<td>YES</td>
</tr>
</tbody>
</table>

In general, it can be said that the technique of producing illusions of depth in pictures also applies to films, television and CGI; the major difference is that these can incorporate the object-motion cue to depth which is congruent with the pictorial cues to depth. The overall position for standard CGI (that is to say all non Virtual Reality systems) is summarised in Table 2.1, showing whether these cues conflict with, or have the potential to conflict with, or are congruent with depth as specified by the pictorial cues. It can be seen that whilst object-motion perspective change is congruent with pictorial information, observer motion, stereopsis, accommodation, and brightness,
contrast and texture gradient information, may still conflict with the pictorial cues. An intriguing aspect of some of the simulator and computer generated imagery literature is the amount of attention paid to the relative strengths of the physiological and motion cues to depth (Doscher, Sperling and Wurst, 1986; Reinhart, Beaton and Snyder, 1990; Baird, 1992; Young, Landy and Malony, 1993, Landy, 1993), and the way in which these cues are combined, when it is perhaps of equal importance to note their potential for conflict in that they specify that the CRT or projection surface is flat.

One advantage possessed by the so-called Virtual Reality systems is that some of this cue conflict has been reduced: to varying degrees these systems incorporate stereoscopic and observer-motion information. While this does add considerably to the power of the illusion of depth or relative distance, the potential for conflict between the Brightness Cues, or between one of them and other cues, is still present. While the question of the brightness cues will be discussed in the next chapter, an indication of the relevance to simulators is appropriate here.

6. Information from luminance and contrast.

In the table above, luminance and contrast gradients were both identified as potential cues to depth. In the natural world, there is a reduction in the luminance of the retinal image with distance, because atmospheric absorption and scatter increase with distance. This is addressed in some simulators by the technique of incremental shading: from a given starting distance from the eye position, all polygons are shaded to coincide with
the background over a specified number of steps. This is reasonably realistic for large virtual terrains, provided the background colour is chosen with care.

There is also that effect of brightness on distance perception in which a brighter object looks larger and/or nearer. Whilst the association between brightness and size may not be valid, that the brighter of two objects looks nearer has been reported by Ames (1949), Gibson (1950), Osgood (1953) (who suggested that contrast served to maximise the effect of brightness and colour differences), Ittelson (1960) Baird (1992) and Padmos and Milders (1992b) inter alia. The relevance of this to real world perception was disputed by Gibson (1950), though he subsequently included luminance gradients in his list of invariant characteristics of the optic array (Gibson, 1966); while Fry, Bridgman and Ellerbrook (1949) and Schor and Howarth (1986) proposed a link between contrast and stereopsis, and Rohaly and Wilson (1991, 1993) suggest that contrast has an influence on depth perception that is prior to that of stereopsis. Ross (1967, 1993), Farné (1977) and O'Shea, Blackburn and Ono (1993) all argue that it is the contrast, rather than the absolute brightness that is the depth cue.

There are at least four other ways in which luminance variations in scenes depicted by CGI do not emulate fully the luminance variations that would have been produced by the natural world scene. First, screen luminance varies across time because of the warm-up time of the screen: measurements taken on the display monitor of the BEST suggest that the warm up process follows an approximate logarithmic function for the first 30
Figure 2.1: Screen luminance change over time.
minutes, with different slopes for each colour, and that stability is only attained after 50 to 60 minutes (see Figure 2.1).

Second, screen luminance can vary over and above programmed differences (Livingstone and Hubel, 1987) due to the technical limits of the hardware. The problem here is maintaining a constant convergence of the three electron beams over the full screen area. In general for screens of intended uniform luminance, the screen centre has the highest luminance and there is a steady drop in luminance towards the edges; this reduction in luminance from screen centre to edge can exceed 35%, Hone (1991). Further, introducing a polygon of a different hue can cause local perturbations in the luminance, and therefore have the potential to change local contrast. If luminance information for distance is used by the visual system, then these unintended luminance variations could modulate the impression of depth from moment to moment, as an object moved across the screen or as the observer moved around the scene.

Third, the pixel size may increase with intensity, ("Blooming") but this, however, varies considerably from monitor to monitor (BYTE, 1988, 1989), and can usually only be seen in polygons of more than 50% of screen area. Its effect on depth perception would be to make the object look closer: qualitatively the same effect as a luminance increment. It should however be noted in this context that Stenger at al (1981) proposed the reduction in luminance, and hence in contrast, of a single pixel representing a far object as a way of partially overcoming the pixel scaling limitation.
Finally, systematic fine grained luminance gradients are not customarily incorporated into CGI; this zero luminance gradient specifies a 'flat' surface at right angles to the line of sight, and, to the extent that luminance information for distance is exploited by the visual system, the impression of depth will be reduced. True, it is possible to generate an apparently continuous luminance gradient on a display monitor and to fill a single polygon with such a gradient; the demands on processing power are such that the time taken to do this would have a seriously adverse effect on the screen update rate. Such luminance gradients may often also be accompanied by contrast gradients; it remains to be clarified whether the critical cue is luminance, or luminance gradients, or contrast, or contrast gradients, or even some combination of these.

7. Other limitations of CGI.

Some specific problems with CGI over and above the general problems of depiction, will now be considered.

7.1 Texture gradients.

As has already been mentioned, the simulator screen can only present polygons which are sized in multiples of one pixel, moreover, it cannot show small circular surfaces, as such, at all. Even if screens of far higher resolution were available, the problem of handling thousands rather than hundreds of polygons would demand a colossal amount of processor power and video memory. This problem is addressed in one military simulator by providing micro-terrains. These are areas of a few hundred square metres,
having more detailed contour and texture information, set within a landscape that is many kilometres square. Now, J.J. Gibson (1950) accorded texture gradients a fundamental status in his classification of depth information because of their prevalent availability in natural scenes. Although sparse texture gradients can be incorporated in CGI, there are severe limits to their faithful portrayal. One suggestion from Stenger et al (1981) was to have a separate texture generator, whose image would then be combined with the perspective image: this would of course confront the absolute barrier of the number of pixels available for display. However, it has also been argued that such textures cannot be abstract, but must be of a familiar or appropriate nature (Chappelow and Smart, 1982; Rolfe and Staples, 1986). Screen texture, deriving from the actual matrix of pixels on the screen, is a different, and an additional, source of potential conflict since it is another specifier of flatness (as will be seen below).

7.2. Field of view and the station-point.

Ideally CGI should provide a field of view of the order of 45-55 degrees, comparable with the field of maximum detail in normal human binocular vision, and the observer should be placed at the correct station-point in order to receive the same pattern of information as would have come from the depicted scene. But often these design criteria are at least partially incompatible: programme an angle of vision to match that of human binocular vision, and the observer at the correct station-point will be so close as to be able to see the pattern of pixels; move the observer away from the display in order to lose this pattern and the observer will no longer be at the correct station-point. Attempts to use a larger screen will usually find that the pixel size is larger and hence the pattern
is still there. The net result is often that a viewing distance of about 2.5 to 3 times the station-point distance is used, resulting in a 'telephoto' effect (see Sedgwick, 1986) for a detailed analysis).

Whilst there are limits on the provision of texture in the scene, the screen itself is not without texture. As has been said above, the image is created by the beam of electrons passing through small holes in the shadow mask. An observer very close to the screen may be able to resolve these tiny spots of colour, separated by the black of the shadow mask, giving a grain or texture effect. Even with the 2.5x distance multiplier from the theoretical station-point, the texture of the pixel matrix can often be resolved, particularly in an area of high luminance. If texture can be regarded as the grain size proportional to the area of the polygon, a smaller area on the screen will have a proportionally larger grain and hence a coarser texture. Move an object further away in the simulated scene and while the proximal image will reduce, the grain will get coarser - the reverse of the natural world, and thus a conflict between two cues. Moreover, a scene component having uniform luminance, even though made up from polygons of differing colours, will show uniform grain - a cue to its being flat when a 3-D scene is sought.

8. To improve the image.

Efforts to improve simulator displays have generally taken one of two paths: that of improving the hardware (not confined to the computer itself) or that of considering the
relative contributions made by particular aspects of the portrayed scene toward a realistic display (upon which the software can have a bearing). Naturally enough, the intended purpose of a given simulator can have a strong bearing on the approach used: one airline now uses a flight simulator computer game to train cockpit crews in operational systems, the visual quality of the display being regarded as adequate for this purpose (Fitzsimons, 1994).

8.1. Hardware improvements and developments.

It has been stated above that many of the cues to depth produce, or are capable of producing, a conflict of information when the display is on a monitor screen. The scene is intended to portray depth, whilst many of the cues specify a flat surface that is perhaps only 1.5 metres in front of the observer. Several simulator manufacturers are now producing or developing projected displays to overcome this. Projection can be onto the front of a reflective surface, or the rear of a translucent surface, and the use of more than one projector can enable provision of more than one channel for scene information. If the images from more than one projector can be combined in some way appropriate to the type of simulator, the total simulated visual field can be sufficiently large that it can be presented at such a distance that the distance viewing effect is reduced or eliminated. The use of multiple channels has the practical effect of changing the limitation on the maximum number of pixels to that of pixels per channel, and thus of polygons per channel.
Projector systems can be combined with collimation systems in order to produce a display that is optically at a great distance. One such system projects a collimated display onto the inside of a large concave mirror (Harris, 1984; Todd, 1988; Kent, 1990). The illusion of depth is very strong, but the lower part of the scene may represent a virtual distance of only a few metres, and this can generate a new conflict. Similarly, in marine simulators using collimated displays, a scene feature at a virtual distance of several kilometres but a real distance of a few metres, can appear at very different bearings to two observers standing side by side; this is often referred to as the problem of simulator parallax. Simulator parallax can also occur in aircraft simulators with collimated displays, although Strachan (1988) considered that the problem was acceptable for tasks where a wide field of view was desirable. Collimated systems can also generate an unwanted perception of the eye position being at a great height, which can lead to inappropriate perceptions of relative distance with near objects (Padmos and Milders, 1992a).

### 8.2. Scene requirements and software.

The approach normally taken is to start from normal human visual perception, to take a specific aspect or cue, and to relate this to the simulated display. This approach may identify a real or potential problem that can be addressed by improvements in hardware, or one that can be resolved by software developments: the use of more efficient program code, or modifications to algorithms. Section 4. above referred to aliasing (the staircase effect) and this makes for an appropriate example.
The virtual scene is represented by polygons, and these will differ in hue and in intensity so as to indicate edges (or boundaries, or contours). Any straight edge must in practice occupy more or less than half a pixel, and be depicted as if it occupied totally, or did not occupy that pixel. This is of no moment when only vertical or horizontal edges are involved, but can affect depiction of an edge of any other orientation. The edge is now stairstepped or jagged, its representation is no longer precise (see Szabo, 1978), and the effect is stronger with higher contrast (Kraft, Anderson and Elworth, 1980). The jagged edge effect does reduce with higher screen pixel counts, but the edge and the pixels immediately adjacent to it are still effectively of lower spatial resolution. Some of the early anti-aliasing algorithms offered a cure which produced a local spatial definition no better than the complaint (Kraft and Shaffer, 1978; Yan, 1985; Magnanat-Thalman and Thalman, 1987). Since any anti-aliasing technique has the effect of blurring the edges to which it is applied, there is the potential for the apparent movement noted by Mather and Morgan (1986) to occur.

Padmos and Milders (1992b) refer to the technique of taking each pixel (or at least the pixels around edges) dividing these into a virtual matrix of sub-pixels - thus enabling a finer definition of the edge - and colouring each pixel with the average of the virtual sub-pixel colours. They then relate this to the maximum acuity of the visual system to determine the minimum size of the virtual sub-pixels in terms of arc-minutes of visual angle. Their findings were that for non-critical tasks, and a pixel subtending 3 arc-min (equivalent to 20 pixels per degree) the sub-pixels were limited to a 2x2 matrix). This is supported by the work of Booth, Bryden, Cowan, Morgan and Plante (1987).
The quest for realism can also see this type of algorithm used in reverse. The American SIMNET system (Bolt, Beranek and Newman Corporation) is used for armoured vehicle training. Such vehicles often create a following dust cloud, and by taking the pixels at and around the rear of the vehicle, creating a local matrix of multiple pixels, and colouring the cells in this matrix by the average of their constituent pixels, a blurred area is produced to simulate the dust cloud. Either of these uses of averaging algorithms must be put into effect at the graphics processor stage of the hardware, and become part of the speed limitations of that stage.

9. Conclusion.

The production of CGI for real time simulation thus requires a degree of compromise. Processor speed imposes a limit on either scene detail, or the area of the virtual landscape, viewing distance must be traded against the visual angle and the point at which the pixel grain is visible, and some of the natural world cues to depth cannot be fully implemented. Moreover, the sharpness of an edge is dependent on its orientation, and the luminance pattern of the depicted scene does not accurately reflect that of the natural world. Arguably, the inability of the screen to depict accurately the luminance and contrast gradients of the natural world, leads to the possibility of conflict. The conflict may be between luminance gradient and contrast gradient, or between these, and other sources of depth information that may specify the spatial layout of the depicted scene. The next chapter will consider those sources of depth information that may be available when CGI are displayed on a CRT, the validity of luminance gradients and contrast gradients as sources of depth information, and the relationship between them.
CHAPTER 3: DEPTH INFORMATION ON THE MONITOR SCREEN.

1. Introduction.

It has already been shown that simulators have limitations in the amount of visual information that can be displayed, so that the depiction on the simulator monitor may often involve some compromise, and that there is a potential for depth cue conflict which can be reduced, but not eliminated, by the design of the simulator environment. In Experiments 1 and 2, it was shown that variation in luminance across the objects in a scene can influence judgements of the spatial layout of that scene.

This chapter will discuss several sources of information that are normally considered to be cues to depth, as they apply to the display on a monitor. Two such sources of information in particular will be examined in detail: the nature of the information from linear perspective, frequently regarded as the most important pictorial cue (Gombrich, 1960, Pirenne, 1970), and one where the amount of information can be variable in amount (Freeman 1966a, b.; Attneave and Frost, 1969); and the information from luminance differences between objects. Consideration of the information from luminance differences will involve the argument as to whether absolute luminance differences are a cue to depth (Ames, 1949; Osgood, 1953; Ittleson, 1960; and with specific regard to simulators, Padmos and Milders, 1992b; J-A Baird, 1992), or whether it is the contrast due to luminance differences that is a cue to depth (Ross, 1967, 1993; Farné, 1977;
O'Shea, Blackburn and Ono, 1994). The argument between the proponents of luminance, and of contrast, bears on discussions of the manner in which different sources of depth information are combined, and approaches to depth cue combination will also be considered.

2. Cues that specify flatness.

Eye vergence is considered a cue to the relative distance of objects in the real world, if they are relatively close (Berkeley, 1709; Swenson, 1932; Hochberg, 1964; Ittleson, 1960). Swenson, (1932), Grant, (1942) and Gogel, Gregg and Wainwright (1961) have all shown that vergence can be used in judging the distance of an object. Opinions differ as to the strength of the vergence cue: Kling and Riggs (1972) holding that it is a weak cue, while Zimbardo (1988) suggests that it is effective to a maximum distance of 10 feet. It can be said, however, that at the correct viewing distance for most drawings, paintings, or simulator displays, the lack of vergence alteration will be a cue to flatness.

Another similar cue is that of accommodation: changes in the focus of the eye. This is probably a weaker cue than vergence; Wundt (1862) claimed to have shown that vergence alone could provide depth information, but this rested on a presumed absence of vergence in monocular vision, which Hillebrand (1894) argued could not be taken as true. A more recent study, in which accommodation was the only source of depth information, concluded that subjects could not use accommodation on its own to judge distance (Künnapas, 1968). Kling and Riggs (1972) argue that the use of both
accommodation and vergence require that other information has been used first, and refer to accommodation and vergence as secondary cues. In any event (chromatically induced variations apart), a monitor display will not normally require a change in accommodation, and again the cue will specify the flatness of the observed surface. If an object on a monitor moves 'away' from the observer, accommodation may occur as a learned response to the movement, but would then require that the observer refocus on the screen, and the momentary accommodation change would have no beneficial effect.

The third cue in this group is that of motion parallax: the way in which near objects will seem to be displaced more with observer movement than will far objects. The relationship of the components in a picture is always fixed, and the lack of differential movement within the retinal image, when the observer's head changes position, is thus another specifier of flatness. On a simulator display, rotating the eye position in the simulation will produce an effect similar to natural world motion parallax; this will, however, be offset by the lack of motion parallax from an equivalent movement of the observer's head, and also on direct monitor displays by the difference in angular extents between the simulators 'eye' and the observers eye.

3. Cues that specify depth.

One information source that is invariably present is that of linear perspective. This has been considered as the most important source of depth information in any scene depicted
on a flat or near-flat surface for several centuries, so much so that it is usually taken as given. Since a line drawing can provide a sense of depth, and an indication of spatial layout, without information from hue, luminance, shading, or interposition, this is easy to understand; the amount of information, and the way in which it is provided, is seldom questioned. However, since linear perspective is a geometrical projection from the scene to the retina, sources of information that are often listed as separate cues, such as relative size and relative height (e.g. Kling and Riggs, 1972) are an inherent part of that projection. Treatment of the components of linear perspective as separate cues may enable an evaluation of the contribution that each component makes, or may facilitate control of the total amount of information in a stimulus; the inter-relationship between the geometric cues will, however, remain.

3.1 Texture and texture gradients.

The boundary between two areas of differing texture can define an edge. It has already been indicated that a simulator display can not normally provide the richness of texture that obtains in the real world, or even that of paintings. To the artist, the reduction in image size of (say) successive stair treads as they recede from the observer, or pictorially as they recede from the stationpoint, is part of linear perspective (Howard, 1988; Gair, 1990); to Gibson (1950), this would be a simple example of a texture gradient. As with relative size, the link between texture gradients and perspective is also a matter of geometrical projection from scene to retina, and has been examined for several angular measures of projected texture (Purdey, 1960; Sedgwick, 1983). For scenes that are sparse in content, it may be more appropriate to consider the change in depicted size of
a line of identical objects as a component of linear perspective, the marginal texture
gradient being ignored. A similar case is that of height in the visual field.

3.2 Height in the visual field.

Height in the visual field (HIVF) is normally regarded as being an influential cue. It
would be more appropriate to speak of height in relation to the horizon, since an object
more distant to the observer will appear to be closer to the horizon. Thus, while objects
on the ground will appear as higher in the visual field with increasing distance, an object
above the ground (shall we say a hot air balloon) will appear lower in the visual field
as its distance increases. Much Chinese art does not employ linear perspective as such,
nor does it provide a conventional horizon - which minimises the negative aspect of the
lack of perspective - but uses a combination of height in the picture plane and familiar
size to produce an effect of depth. In the conventional depiction employing linear
perspective, HIVF can be said to provide two pieces of information: the relationship
between the upper and the lower extremes of an object, and the horizon. These do not
provide any absolute spatial location save in the case where the bottom extreme is never
higher than the horizon, regardless of its distance from the observer; this indicates that
the lower extreme is on the ground plane.

3.3 Relative size and familiar size.

If the distance between an observer and a known object increases, the size of its retinal
image (strictly the visual angle subtended by that object) will reduce but not the
observer's perception of its size based on knowledge of the object. That the known object now subtends a smaller angle for its known size can be considered as a cue to depth, but the information from familiar size and relative size may conflict (Hochberg and Hochberg, 1952). This conflict has been offered as an explanation of several of the geometric optical illusions.

In 1954, Tausch proposed that we learn to correct for depth in scenes depicting a 3-Dimensional world as a way of seeing the 'real object' - the intended percept - in these displays. If a cue in a 2-D display should trigger an inappropriate correction, an illusion would result. Tausch (1954) saw the process as one which tended to bring angles nearer to being right angles, thus increasing acute angles and reducing obtuse ones. This approach relates directly to linear perspective. Kristof (1961), argued that it was perspective itself that acted as the trigger for a constancy process that sought to restore the "real object", with illusions resulting from the conflict between the constancy effect and the known fact that the display itself was flat. Gregory (e.g. 1963, 1968, 1970) extended the effect of size constancy into his theory of constancy scaling, and suggested that this was triggered in two ways: primary constancy scaling triggered by perspective, and secondary constancy scaling set by the integration of the available high level depth or distance cues.

4. Linear perspective in depiction.

The technique of linear perspective projection (from the Latin perspicio, "I look
through") in its present form dates from the fifteenth century. The earliest known description is that given by Alberti in his *Della Pittura* of 1436 which referred to "artificial" perspective. The terms used today: picture plane (which Alberti compared to a window frame), fixed spectator point or station point, central vanishing point, distance points, etc., can all be found in this work. Leonardo da Vinci is generally credited with the use of a sheet of glass as the picture plane, and by the early sixteenth century, Durer had published a formal text on perspective and proportion. Durer introduced several mechanical aids for perspective drawing, one of which can be seen as the forerunner of computer techniques for producing three dimensional plots from contour coordinates.

From the mid-sixteenth, to the late nineteenth centuries, many mechanical and optical aids to perspective drawing were developed, varying in their ingenuity, yet all having a common aim: the accurate depiction of a part of the natural world, as seen from one particular location, onto a plane surface. The following definition of perspective from Chambers Encyclopedia of 1895 would be acceptable today:

"the art of representing natural objects upon a plane surface in such a manner that the representations shall affect the eye in the same way as the objects themselves" (Chambers, 1895, vol VIII, pp74-75)."

Thus, linear perspective is one form of projection of a three dimensional scene on to a two dimensional surface. Another perspective transformation is possible, and will be referred to later.
4.1 The importance and limitations of linear perspective.

Linear perspective is generally held to be the single most influential depth cue in scenes depicted on a plane surface, (Gombrich, 1960; Pirenne, 1970; Hagen, 1986; Kubovy, 1986; for example) and yet this cue is one that should only function properly from one specific position for any depiction, and then only if viewed with one eye. Linear perspective is a projection from one single point - the station-point - and two human eyes cannot occupy the same physical position. Despite this, our perceptual system seems quite tolerant of minor alterations in the viewing distance, and of the lateral separation of our two eyes (Rosinsky and Farber, 1980; Kubovy, 1986).

Kubovy (1986) argues that the effect of linear perspective is particularly robust, and can tolerate minor displacements from the station-point. He also argues that the brain can infer the correct station-point from the visual information available, and then process that information as if it came from the correct station-point. The notion is not new; Wells (1792, cited by Ono 1981), devised a method of locating what came to be known as the cyclopean eye. This was situated just behind the midpoint of the line connecting the two eyes. Later this came to be known as the sighting egocenter (Howard, 1982), and Kubovy (1986) has developed this into the concept of the moveable egocenter; these 'egocentres' being psychological constructs of the station-point.

Drawing on the work of Lee and Aronson (1974) and Lee and Lishman (1975) as suggesting that visual information is dominant where there is conflict between receptor
systems, he discusses a study (Kubovy, 1986, pp154-158) which supports the view that it is easier to compensate, in the processing required to maintain the egocentre construct, for a vantage point displaced linearly, than for one rotated. Certainly, on some simulators, the combination of a rotating eye position and linear displacement can lead to a degree of disorientation.

Another aspect of linear perspective is that of the distortions that occur toward the margins of the field of view, unless the field of view represents a narrow visual angle. These distortions, sometimes referred to as 'Leonardo's Paradox' stem from the geometry of linear perspective projection, and can result in objects toward the edge of the field of view being depicted as larger than identical objects in the centre of the field of view. The normally robust effect of linear perspective will break down both with a separation of viewing point from station-point, or with an increase in the angle of view, the two conditions combining to increase the distortions. Olmer (2 vols.: 1943, 1949) suggested a horizontal visual angle of 37 degrees, and a vertical visual angle of 28 degrees, referring to this as Perspective Normale. Sanders (1963, Experiment 3, pp49-52) using a display of lights, and Finke and Kurtzman (1981) using a fixation point that moved away from the centre of a display of radial lines, suggest that 34 degrees and 35 degrees respectively are the limits of the effective horizontal visual angle.

Dubery and Willats (1983) note that the distortions commence when the visual angle is around 25 degrees, and discuss the use of 'synthetic perspective': the use of a curved
picture plane (see Doesschate, 1964, for an extensive account).Whilst it would seem appropriate to use this synthetic perspective in those simulator systems that project an image onto a curved screen, this form of perspective requires that many straight edges be shown as curves, and this would in turn lead to the problems of aliasing referred to in the previous chapter. In practice, modern projection systems do not exceed a 30° angle of view for a single channel; five channels enabling a 150° total horizontal field of view, when 140° is the desirable minimum for most pilot training tasks (Strachan, 1988).

4.2 Information from perspective.

One of the most common methods of specifying the location of a point in 3-D space is the Cartesian co-ordinate system, with the three axes referred to as x, y and z. The first two correspond to the axes on an x-y graph, with the z-axis values reflecting distance from the observer or reference point.

The simplest form of linear perspective is that of ‘Parallel Perspective’, a special case of ‘Single Point Perspective’. Visualise looking along a floor that is tiled in a chequerboard pattern. The tile edges are either parallel to the x axis and thus to each other, or parallel to the z axis and to each other. The z parallels appear to converge with distance, and if the floor is large enough will eventually appear to meet at the Vanishing Point (VP). As the tiles recede from the observer, the size of their image on the retinae reduces in proportion to the angle subtended by each tile. This progressive
reduction thus offers a texture gradient, Gibson (1950) using just such an example, but also involves the cues of relative size and relative height (HIVF), Bruce and Green (1985).

The more general form of ‘Single Point Perspective’ can be illustrated by considering a rectangular solid as shown in Figure 3.1.a, where two faces can be seen, and where \( x \) and \( y \) are both parallel to the picture plane. The \( x \) and \( y \) edges remain parallel, while those running in the \( z \) direction appear to converge to the VP.

Given a case where only one axis is parallel to the picture plane - look at a vertical edge of the solid - and only the \( y \) edges will appear parallel. The other edges are now functions of \( x \) and \( z \), with those lying on each side of the \( y \) edge converging to a separate vanishing point, normally referred to as a Distance Point (DP), as shown in Figure 3.1.b. This is ‘Two Point Perspective’. If the imaginary solid is now considered as being a tall building, and the axis of vision is toward its top, none of the edges are now parallel to the picture plane: there are now three DP’s, and we have ‘Three Point Perspective’. There are therefore three different forms of simple perspective that can apply to a single rectangular solid object. If the scene, whether in the natural world or depicted on a simulator display, contains more than one object, then the perspective is considerably more complicated.
Figure 3.1: Single and two-point perspective.
In the case of the single object described above, it can be said that the projection of any pair of converging parallels will meet at their VP or DP, or that they lie on (or have points of correspondence with, or "fit") lines radiating from the VP or DP. Where the scene contains a number of identical objects - as will several of the stimuli used in the experiments to be reported here - then not only do the converging parallels fit lines radiating from the VP or DP, there is also a second type of fit. The parallels hidden from view that are normal to the picture plane may also be considered as converging, but only those endpoints that are the visible apex between two edges, parallel to the picture plane, can be seen.

The smaller an object, the less information is available from the convergence of its parallels (Freeman, 1966a, b; Attneave and Frost, 1969), since these will be shorter, making it more difficult to judge the degree of convergence and thus the vanishing point. On this basis, the strength of perspective information can be influenced by the absolute size of the objects in a depicted scene. Weinstein (1957), Smith, Smith and Hubbard (1958), and Wallach and O’Leary (1982) have all shown that HIVF can influence perceptions of both relative size and absolute size, and thus also affect the strength of information from perspective. The five studies just referred to have all taken the approach of breaking down a geometrical projection into components (see section 3 above), and regarding each component as a separate cue. Thus, if perspective is narrowly defined as the information from the edges of objects in a scene, reference to the strength of perspective as a cue to depth can relate only to edge information; a
broader definition enables better assessment of the type and amount of information available.

On the narrow definition, the amount of perspective information could be considered as the total amount of edged information available from any given scene. In the natural world, the visual scene is often so complex that there can be many thousand edges and many VP’s and DP’s, a staircase may have one VP or DP defined by the edges of the treads and risers (or by their fit to the lines radiating from that point), and another VP or DP defined by the apices of those treads and risers. The stairwell may well offer another VP, while the stairway that turns a corner will add yet more points to the scene. While the simulator display is far less complex, the generation of any depicted scene is based on linear perspective, and the adequacy of perspective information is always assumed. The experiments reported in the next chapter will involve the manipulation of perspective information on the basis of the amount edge information, and by variations to HIVF.

5. Information from luminance.

There are several ways in which luminance may provide depth related information. Luminance contrast is one indicator of an edge, and without edges there would be no information from linear perspective. Edge definition apart, luminance contrast and absolute luminance have each been proposed as cues to depth, and even in the sparsely detailed scenes of a simulator display, there are sufficient components to permit both luminance gradients and luminance contrast gradients to be present, even though such
gradients may not be faithful to an equivalent natural world scene. Although the Ames Demonstration 18 - the two balloons - shows that a change in luminance can change observers' perceptions of distance (Ames, 1949), the luminance change also effected a change in the luminance gradient from foreground to background, and thus the change in luminance gradient may have been the operative cue to depth.

Light energy from a point source reduces as the distance from that source increases, and does so as the inverse square of the distance. In the natural world, and on the simulator display, surfaces or objects are far more common than point sources; the area of the retinal projection of these surfaces or objects also reduces with distance as the inverse square of the distance. The luminance of the object or surface, being a measure of the intensity per unit surface area, will thus remain constant. Despite this, there have been several attempts to separate intensity from area, or to treat luminance as if it was intensity.

Pokorny and Smith (1986) offer the example of a star as a natural point source, and emphasise that few natural light sources approximate to a point source. They do, however, accept Teele's finding that the inverse square law will operate with an error of less than 1%, provided that the maximal dimension of the extended source is equal to or less than 10% of the distance at which measurement is made (Teele, 1965). Pirenne (1967) has stated that every point on a surface can be considered as a secondary light-source; if, however, a surface is considered as containing a large but finite number
of points, the density of those points will also change as the distance from the surface changes. Sperling (Schwartz and Sperling, 1983; Dosher, Sperling and Wurst, 1986) regarded the inverse square law for points as one that translated into an inverse linear law for lines:

"At the observer's viewpoint, the observed intensity of a self-luminous line decreases in direct inverse proportion to the distance of the line". (Dosher, Sperling and Wurst, 1986, p975)

The Sperling studies are of particular interest in that the work related to the Necker Cube illusion using a computer driven display. In geometrical terms a line may have the dimension of length, but to be visible it must also possess width, and thus become (and behave as) an area; on a simulator display, any line must have a minimum width of one pixel, and changes in the distance of that line would scale the width of the line subject to the pixel scaling limitations already discussed.

Appealing to optical physics, in order to show that luminance should not function as a depth cue, assumes a point by point mapping from retinal image to percept - that we 'see' the retinal image. In reality, we see with the aid of the retinal image (Neisser, 1974), and this is constantly changing. The saccadic movements of the eyes, and the minor body movements due to muscle tremor, will each cause fluctuations in the retinal image; our perception of the scene that led to the retinal image will remain stable, indicating some degree of processing between image and percept.
If the compensation between retinal image size and retinal image intensity, over distance, is such that the luminance of an object cannot function as a cue to its distance, the same cannot be said for brightness as the percept of the luminance of that object. In a comment on the Ames Demonstration 18, Woodworth and Schlosberg said:

"Just why an increase in brightness makes an object seem to approach is not particularly clear from a functional standpoint - or from any other."

(Woodworth and Schlosberg, 1954, p490)

an explicit acceptance of brightness as a cue to distance.

Woodworth and Schlosberg (1954) state that increasing the visible area of a surface from a point, to the size of half a degree of visual angle, will increase the apparent brightness of that surface. This can be translated into terms of possible natural world experience. If one takes a plane surface normal to the axis of vision of 10 metres square this will subtend less than half a degree at distances greater than 2,000 metres. Ten metres square is the size of a typical detached house, which would normally be visible in daylight at up to 3,000 metres or more, incidentally a distance within the normal scope of many simulator systems to depict such a house. Of course, 3,000 metres is sufficiently far, in some environments, for atmospheric perspective to influence perceptions of distance; atmospheric perspective, as a cue to distance, will be considered in the following section.
General claims that brightness is a cue to depth (Osgood, 1953; Ittleson, 1960; J-A Baird, 1992; Padmos and Milders, 1992b) would seem to rest on the Ames Demonstration 18 (Ames, 1949). In this demonstration, size and luminance were varied, with judged size or relative distance as dependent variables; distance was not varied, and thus Ames (1949) can not be said to provide a complete statement of the link between brightness and distance, only of its existence. Gibson (1950) accepted that laboratory demonstrations of such a linkage had been made, but did not name the researcher, and doubted their relevance to real world situations.

Two studies that did vary distance with observers' judgement of brightness as the dependent variable were those of Brunswik (1929) and Burzlaff (1931). Each of these experiments involved the matching of grey patches viewed through a reduction screen, and each found a reduction in brightness with increasing distance; in these two studies the aperture in the reduction screen was fixed so that the angular extent of the target did not alter, although the area of target visible through the aperture did alter. These studies demonstrate that changes in luminous energy can be perceived when the size of the retinal image is held constant. Landauer and Epstein (1969) used a self-luminous disk over a range of distances, required each of their observers to make a single judgement of distance, and found that estimated distance increased across observers as the angular extent decreased as would be predicted by the size-energy compensation principle. In contrast, a similar study by Gogel (1969) found that judged distance did not change with changes in angular extent. Gogel (1969) obtained this finding from the first judgement of each of his observers, in a task that required repeated judgements; when all...
judgements were considered, his results matched those of Landauer and Epstein (1969). Both the Landauer and Epstein (1969) and Gogel (1969) studies were conducted in an outdoor setting, and other depth information must have been available from the environment; in the absence of the precise detail of such information, one can only speculate that this may have led to the disparity between the Landauer and Epstein (1969) results, and those of Gogel's (1969) first judgements.

None of the four studies referred to in the preceding paragraph offered perspective information from the stimulus, and size, distance and angular extent are all related within linear perspective. The relationship between brightness and judged distance demonstrated by Ames (1949), and the change in perceived brightness with a change in angular extent (Woodworth and Schlosberg, 1954), argue that a relationship between perceived distance and perceived brightness exists, and thus that differences in brightness may well have the potential to function as a source of distance information.

Before leaving the matter of point and extended sources, it must be emphasised that this is an aspect of simulators where they do not accurately reflect the natural world. Each pixel is small enough to be considered as a point source at normal viewing distances, and the pixels that make up a given surface are primary sources, but will not vary in luminance or angular extent with depicted distance. The hypothetical 10 metre square surface referred to earlier could - depending on distance - be depicted as 100 pixels square, or 50 pixels square, or 10 pixels square or less. The emitted energy will relate
directly to depicted size which, while a function of depicted distance, will be affected by the pixel scaling problem referred to in the previous chapter.

6. Aerial perspective.

One cue to distance that does not seem to be contentious is that of aerial perspective - the way in which, in the natural world, light energy is affected during its passage through the atmosphere. Two physical processes are involved: absorption of light energy, which is increasingly effective on light of longer wavelengths, and will directly affect light passing from a distant object to an observer; and diffraction (or scatter) which affects the shorter wavelengths more than the longer ones, and as light from a distant object is scattered away from an observer, light from the sky is scattered into the observer’s line of sight. The net effect is that objects in the distance appear less bright and offer less contrast with their background (Minnaert, 1940; Eldridge and Johnson, 1953).

The rate of contrast change over distance was explored by Fry, Bridgman and Ellerbrook (1947, 1949), Duntley, (1948) and Middleton, (1952) as a matter of physics, and has been a major focus of the work of Ross since 1967. Aerial perspective as a cue to depth was utilised by artists long before the Renaissance painters developed the use of linear perspective, and was given some prominence by Bishop Berkeley (1709/1910) as an example of experience affecting perception. There are a number of reports of people
PLATE 2: ATMOSPHERIC PERSPECTIVE

Top: View NW from the Hogs Back on the A31, looking toward Aldershot.
Bottom: View ENE from Planada on California Hwy 140 to the Sierra Nevada.
Casual judgements of distance to the horizon are between 7 and 11 miles for the top view, and 18 to 20 miles for the bottom view. The correct distances are 11 miles and 40 miles.
who live in smoggy cities underestimating distances when in clean air (Bohren, 1987; Goldstein, 1989). Examples of atmospheric perspective are shown in Plate 2.

Ross (1967) studied aerial perspective at short distances (up to 200 metres) in clear and foggy conditions, and then through a water tank (Ross, 1968, 1971), finding that apparent distance was a linear function of the logarithm of the luminance contrast, if the direction of the contrast was ignored. When contrast direction was considered, observers’ judgement of target distance increased with a decrease in target luminance if the target was lighter than the background, while the reverse was true if the background was lighter than the target.

O’Shea, Blackburn and Ono (1993) argue that contrast on its own is an effective depth cue that simulates the optical effects of aerial perspective. They required a judgement as to which of two equally sized foreground patches (of 19 cd/m² and 96 cd/m², or 41.2 cd/m² and 74.5 cd/m²) appeared nearer when viewed against a background varying from 0.10 cd/m² to 110 cd/m². They found that the darker target patch appeared nearer when the background was lighter than both targets, and further away when the background was darker than both targets, concluding that the apparent depth effect was due to contrast.

Several of the reports which hold that luminance is a cue to depth, were based on viewing two surfaces of equal size but varying luminance, or of equal luminance but
varying size or distance (Ames, 1949; Gibson, 1950; Reinhart Beaton and Snyder, (1990), and presenting the stimuli against a black background. If the luminance of a light foreground is varied, and the background is dark or black, luminance and contrast will co-vary; the apparent effect of luminance variation on depth can then be explained in terms of contrast variation following Ross (1971) or O'Shea et al (1993). This, however, is to assume that it is only the variations in the illuminance of areas of the retinae that lead to the perception of depth, whereas O'Shea et al make it clear that there is at least a possibility that the relationship between depth and contrast is mediated by apparent size.

That the apparent size of a square area increases with an increase in contrast has been shown by Weale (1975) and by Erning, Gerrits and Eijkman (1988). O'Shea et al (1993) modified the task referred to earlier in this section by varying the size of one of their foreground patches through a range of +/- 4%, similar to the range across which Weale (1975) and Erning et al (1988) found a size variation due to contrast. O'Shea et al required both a judgement as to which patch was nearer to the observer, and an absolute judgement of the distance between the two patches. They found that the size information would support, or compete with, the contrast information, and found a relationship between size and contrast similar to that found by Weale (1975) and Erning (1988). O'Shea et al raise the possibility that a low-contrast stimulus may appear to be farther away simply because it appears to be smaller than a high-contrast stimulus. Thus, a high-luminance stimulus could appear to be nearer than a low-luminance
stimulus if it appears larger due to a higher contrast with its background, rather than through the difference in luminance alone.

Negative gradients, where luminance or contrast reduces with increasing distance, would support the information from linear perspective by simulating aerial perspective. The position when one gradient is positive and the other negative is not so clear, and both Ross (1993) and O'Shea et al (1994) have shown that the direction of a contrast gradient can influence judgments. A gradient (contrast or luminance) the reverse of that from natural atmospheric perspective would conflict with linear perspective, and with another gradient (luminance or contrast), and it is easy - whether by design or accident - to create situations on a simulator display where contrast gradients and luminance gradients can support or conflict with each other, and with linear perspective.

7. The validity of size judgements.

In the two preceding sections, evidence has been cited to indicate a relationship between the perceived size of an area and its brightness, between perceived size and luminance contrast, and, to a limited degree, between the brightness or luminance of an area and its perceived distance. As with familiar size, apparent size was first suggested as an indicator of distance by Berkeley (1709/1910). Again, the argument rests on the geometry of the retinal image: if one of two presumed identical surfaces appears larger, it is presumed to be nearer to the observer. This rests on the presumption of equality between the two surfaces: to be valid, this assumption requires either prior experience,
or the availability of other information (see Hochberg, 1971, or Sedgewick, 1986, for extensive reviews). The effect of contrast on judgements of angular extent size referred to above is one reason why apparent size may not always be a valid cue, the accuracy of judgements of visual angle is another, and the 'irradiation illusion' offers yet a third reason.

The quality of judgements of visual angle was investigated by Gilinsky (1955) who required subjects to adjust a triangle to match the angular extent of a target triangle presented at distances over a range of several hundred metres. Her results showed a set of adjustments that tended to overestimate the size of the far object as its distance increased. Later studies of this type have been conducted at shorter distances, (Carlson, 1962; J.C. Baird, 1963; Ono, 1966) have shown a similar tendency. In contrast, Rock and McDermott (1964) found that subjects could accurately match the angular extent of one self-luminous triangle to another, when the two triangles were viewed in a totally dark room. Kling and Riggs (1972) conclude from this that inaccuracy of matches of retinal extent is due to the availability of other information.

The experiment conducted by Gilinsky (1955) was conducted in a natural world environment (a large field) and the full range of cues to depth and distance were therefore available to her subjects. Studies where the depth and distance information was reduced have shown much better judgements of angular extent (Holway and Boring, 1941; Lichten and Lurie, 1950; Over, 1960). The Rock and McDermott (1964) study
mentioned above combined the method of matching the visual angle of two stimuli at different distances, with requiring estimates of their relative distance. Finding that the judgements of angular extent were generally good, but that judgements of relative distance were poor, they concluded that their observers were making judgements based on the perceived angular, rather than the perceived physical extents.

It is generally accepted (Sedgwick, 1986) that judgements of the physical size of an object remain fairly accurate regardless of changes in distance, and hence of visual angle: the phenomenon of size constancy. In information rich environments such as that used by Gilinsky (1955), overconstancy can occur (Gibson, 1950; W.Smith, 1953; Joynson, Newson and May, 1965), and has also been noted in indoor experiments at shorter distances (Holway and Boring, 1941; Chalmers, 1952; Carlson, 1960, 1962;). A common factor in all these studies has been the use of the far object as the referent, with the near object being adjusted or judged relative to the far object, and a finding that the size of the far object is over-estimated. In real world situations, it is far more likely that the far object will be judged relative to the near; for example, combat riflemen are taught to judge distance by comparing known visual angles (average height, or waist to shoulder height) subtended by the target against the known angle subtended by the front sight blade of the rifle - effectively a use of familiar size. In formal studies (see Sedgwick, 1986) most of the evidence suggests that familiar size will affect judgements of distance.
In the simulated environment, the depicted size of an object is determined by mathematics and moderated by the pixel scaling limitation, and the amount of depth information available is substantial. If the depicted scene does convey a realistic impression of depth, it seems reasonable to suppose that errors in the judgement of visual angle comparable to those noted by Gilinsky (1955) may occur when comparing near object to far. Since one component of linear perspective depends on the projection of lines from edges or points on the depicted surface of an object to the vanishing point, any misjudgment of angular extent has the potential to affect a judgement of spatial layout derived from linear perspective. One effect that can affect judgements of size is the irradiation illusion.

The irradiation illusion has a long history, caused problems for the early astronomers, and was discussed in detail by Helmholtz (1864/1911) who described it as:

"highly illuminated areas appear to be larger than they really are, whereas adjoining dark areas appear to be correspondingly smaller" (p 186).

The light area 'bores' or 'irradiates' into the dark, and a brighter area is supposed to irradiate more. This phenomena is frequently ascribed to the presence (or absence) of Mach bands (Mach, 1865, cited in Ratliff, 1965). These bands may be seen where a light and a dark area are separated by a gradation of brightness running from one to another. The conventional explanation for these bands are the processes of lateral inhibition and lateral facilitation within the retina, Hartline, Ratliff and Miller, 1961;
Ratliff, 1962, 1965; Robinson, 1972. Although the light and the dark areas each display a band, Fiorentini and Radici (1958) have shown both that the two bands are not equal - the light band remaining constant but the dark band growing darker with an increase in the steepness of the gradation - and that the light band seems to straddle the zone of change from light area to gradation, whilst the dark band lies wholly within the dark area. Where there is a bright/dark border rather than a gradation, different effects have been reported: Von Bekesy (1968) stating that the appearance of bands will depend on the point of fixation, and O'Brien (1958) demonstrating that perceived differences in brightness can be the reverse of what the actual differences in luminance should give. Although much of the research into Mach Bands has employed rotating disks, McDougall, 1903; McCullough, 1955; Bergstrom, 1966; Richards, 1968; there is more recent evidence that the effects can also obtain on static displays with rectilinear stimuli, and the conditions necessary for the Fiorentini and Radici (1958) findings are usually present on the CRT display.

More recent work on the irradiation illusion has been carried out by Gregory and Heard (1983), Morgan, Mather, Moulden and Watt (1984) and Mather and Morgan (1986). The study by Gregory and Heard (1983) showed that the illusory size difference could reverse at low contrasts, and both this study and that of Morgan et al (1984) refer to conditions under which apparent movement of an edge could occur - Gregory and Heard (1983) with rapid increases in brightness, and Morgan et al (1984) with a rapid change in the blur profile of an edge. Each of these conditions can occur on a simulator monitor, notably when anti-aliasing techniques are used to smooth a diagonal edge.
8. From cue conflict to illusion.

It will be seen from the above that there are a number of cues that can be incorporated into the depiction of a scene, each of which can give an impression of depth. If more than one is used, there need be no conflict between them, but each can offer support to the others and make the impression more powerful. Given the brush of a great artist, however, they can be made to conflict one with another in such a way that the impression of depth is still compelling, but the observer is now uncertain as to which parts of the scene are near and which are far. Salvador Dali was one such artist, and his Christ of St John of the Cross is one such picture. All the depth cues given above are used, but used in such a way that the background can become the foreground, and foreground become background, as the focus of attention moves around the picture. A similar technique, albeit with a less striking effect, had been used in Guido Reni’s fresco Aurora some three centuries earlier. If this conflict between cues can occur when given the richness of information in a great painting, it would seem reasonable to expect such cue conflicts to influence the perception of spatial layout in the much simpler scenes on simulator displays, which do not usually offer the information from texture or shading that can be incorporated in a painting. The illusion of depth will remain, but the perceived spatial layout may not be that intended by the scene designer.

The simulator display is a flat projection of a three-dimensional scene, and several theories of the optical illusions assume that the geometric optical illusions are interpreted by the perceptual system as being flat projections of three-dimensional displays. Thierry (1896) argued that the Muller-Lyer figure could be viewed as being the projection of a
carpenter's trestle viewed from directly above. Now the legs of a trestle are fixed, and the included angle between them is constant, but the vertical projection of that angle will change dependent on their angle to the vertical; thus, any estimation of one angle must also reflect an estimation of the other, and such judgements go beyond the influence of any orientation detectors in the perceptual system. The Zollner, Muller-Lyer and Ponzo figures have all received much attention in respect of misjudgments of angles of alteration to the angles between lines, and those explanations that seem to satisfy the effects of one figure will often not seem to do so for another (see Robinson, 1972, for an extensive account). The more generalised approaches have looked not at the specific illusory figure but at the underlying process, and bear on the more general question of the manner in which different items of depth information are integrated or combined.

9. Cue combination.

Before considering those general theories of optical illusions that require a process of interactions, or cue combination, it is necessary to distinguish two different functions of one source of information: the more general function of a cue to depth, and the specific function of an accurate (or near accurate) definition of spatial layout. The two pictures in Plate 2, earlier in this chapter, indicate how atmospheric perspective can be a powerful cue to depth without offering precise distance information. The most simple model of depth cue combination is that of Bruno and Cutting (1988) who proposed straight cue addition (after weighting each cue): the more cues available, the greater the sense of depth. Of course, increasing the amount of information available should also
lead to a better definition of spatial layout. Other models, as will be shown below, also involve some process of weighting the individual cues before they are combined.

Any representation of a 3-dimensional scene on a flat surface offers cues to flatness - the absence of depth - which the observer will usually set aside. With the reduced information available from a scene depicted on a monitor, those cues that are available may assume greater prominence: as with many illusions, an inappropriate cue may be given an undue value. This is not confined to flat surfaces: illusions can occur in the natural world (Fisher and Lucas, 1969), sometimes with tragic consequences. A mid-air collision near New York in 1965 cost four lives, and injured 49 others, and was officially ascribed to an instance of the Poggendorf illusion triggered by sloping cloud tops. The richness of information available at ground level was not available above the clouds.

Three general theories regarding optical illusions have developed into more general approaches to cue combination. Taylor’s weighted assumption (Taylor, 1962a,b) stated that an observer would use, and evaluate, all available information before making a judgement. Assimilation theory (Pressey, 1970, 1971) started from the principle that if a range of values is available to the senses, any judgement of those values will tend toward their mean. Every additional set of values would complicate this averaging process, and Pressey proposed that the observer would attend only to a number of attentive fields (specific items of information), and that it would be only this information
that would be processed. Adaptation theory is primarily the work of Green (Green and Hoyle, 1964, 1965; Green and Stacy, 1966) and assumes that the stimulus is also compared to a set of stored norms which result from the observer’s normal adaptation level, thus applying some form of weighting to the inflow of information.

While the weighted assumption, assimilation and adaptation theories all agree that depth cue information is weighted, none makes explicit the manner in which the weighted information is combined into a single percept. Assimilation theory could, for example, deal with a conflicting cue by excluding it from those being processed, so that the averaging process deals only with mutually supporting cues. Such a process could exclude those features of a simulator display that specify flatness, and concentrate on those that specify depth in the depicted scene. For the other two approaches, the precise nature of the mathematical process would have a great influence on the result: if one cue is given a negative weighting, the sum of all cues divided by their number would give a different result to subtracting the negative cue from the mean of all positives. One method of handling the mathematics of the combination has been proposed by Landy and his colleagues (Malony and Landy, 1989; Landy, Malony, Johnston and Young, 1991; Young, Landy and Malony, 1993; Landy, 1993).

Landy et al (1991) propose that each cue is first evaluated, as far as possible, in isolation. Following this, each cue is evaluated against all other cues, effectively making a two stage weighting process that can increase the weight given to a weak supporting
cue, or downweight a cue that is strong but discrepant. The final percept is the mean of the weighted cues.

None of the theories above offers a starting point for the process of weighting the cues, save for that of Landy et al (1991) who first treat each cue equally and independently. Pirenne (1970) has proposed linear perspective as the prime source of information for plane representations of 3-dimensional scenes, with the implication that other cues are subordinate to perspective. If contrast information is extracted at a very early stage as proposed by Rohaly and Wilson (1991, 1993), and contrast in some form is necessary in order to specify the edges needed for linear perspective, then contrast has the potential to be the prime information source. This need not be luminance contrast; while some researchers have argued that colour contrast, on its own, does not provide an adequate cue to depth, Lu and Fender (1972), Gregory (1977), De Weert (1979) Livingstone and Hubel (1987), others have shown that colour differences do play a role in depth perception, but that this information is used less effectively than that from luminance, Treisman (1962), Julesz (1971). McCain and Karr (1971), using a Howard-Dolman apparatus, found no effect from luminance, but concluded that colour was a cue for depth, while Jordan, Geisler and Bovik (1990) have shown that there can be conditions where the luminance and chromatic cues are used with equal efficiency, a view supported by Trosianko, Montagnon, Le Clerk, Malbert and Chanteau (1991). If two cues can be used with equal efficiency, but are opposed to one another, one needs to be selected as the more relevant source of information and given a greater weighting. This
can be done by the two stage process proposed by Landy et al (1991), or by simply processing each item of information in parallel.

Eiser (1994) holds that it is implausible to consider that the brain operates as a serial processing system, and the concept of visual information being processed in parallel channels is not new: Livingstone and Hubel (1987) cite several neurological studies over the last twenty years that confirm the existence of separate channels. Pohl (1973), Ungerleider, Galkin and Mishkin (1983), and Rybak, Golovan and Gusakova (1993), have all argued for at least two major channels handling object recognition, and object location: the 'what' channel and the 'where' channel, this last obviously dealing with matters of depth. A 'where' channel would be equally involved in handling matters of spatial layout in the natural world, and where a scene is depicted on a simulator display, even though the information from a particular cue in a simulator display may be at variance with its strength in the natural world.

10. Conclusion.

Consideration of the studies above can lead to a number of conclusions. There is evidence presented so as to show that an increase in luminance is equated with a reduction in distance. There is also evidence presented so as to show that it is the increase in luminance contrast that is equated with a reduction in distance. Warren (1958) suggested that there is an experiential component in judgements of physical intensity, several of the general theories of optical illusions assume that prior experience
is involved at some stage in the process, and prior experience of aerial perspective was an essential component for Bohren (1987) and Goldstein (1989). A common factor in many of the empirical studies above is that there are, at most, two sources of information available on which judgements can be made: luminance differences between areas in the stimulus scenes, and size differences between these areas. In the natural world, and even in the less detailed virtual world of the computer controlled simulator, there is normally a much greater range of information sources which can have a bearing on any perception of depth. However, these cues may not be of the same strength, or may conflict one with another, and in turn be interpreted with reference to past experience. Such differences between cues may be dealt with by weighting, and variations in the strength of one cue should reflect on the weighting given to the others. If the process of cue weighting has to handle one conflicting cue within a small set of cues, the possibility that a false percept of spatial layout will result. Since several of these cues have their origin in luminance variations (or luminance contrast variations), or are related to such variations, the next set of experiments will seek to control the amount and type of depth information available. Manipulating both the luminance of objects in the display so that luminance information supports, or conflicts with, luminance contrast information, and at the same time controlling the amount of information from linear perspective should establish if conflicting information can change perceptions of spatial layout.

The three experiments in Chapter 4 will also seek to avoid relating a near object to a far object (see Section 7 above), by requiring judgements between a variable line and a
reference line of objects as to which line is the longer. As with the Rock and Macdermot (1964) study cited above, two measures could be obtained from such judgements: accuracy of judgement, or relative judgements as influenced by the experimental manipulations. In the context of cue conflict, assessment of the effect of the manipulations on the judged length of the variable line would seem the more appropriate measure.
CHAPTER 4: THE COMPARISON TASK EXPERIMENTS.

1. Introduction.

The three experiments in this chapter have involved two major changes from Experiments 1 and 2. First, the type of judgement required from the observers was changed from one of judgement of relative position, to one requiring comparisons between two rows of objects. Second, the amount and type of information available to the observers was manipulated.

1.1. The task changes.

The two previous experiments each used stimuli scenes that consisted of a set of three objects, and tasks that concerned observers' judgements of their relative position one to another, and, in the second experiment to their orientation on one plane. Depth information came from luminance differences between the objects (available as both luminance and contrast gradients), and from linear perspective; some conditions in Experiment 1 also included the partial occlusion of one object by another. Thus, while the scenes did depict a scene in depth, the available information could only locate the objects within the scene relative to each other. Measurement of the influence of luminance variations was based on the perceived spatial relationship of the objects, not on any absolute reference to the observer or to another group of objects.
The data obtained from Experiments 1 and 2 applied only to the spacing between the objects, and not to the perceived length of the line of objects. Thus, the results of the preceding studies have only shown that luminance variations can affect perceptions of relative spatial layout. To say that in a line of objects A-B-C, B appears to be nearer to C than to A, does not say how far apart A and C appear to be, or even to what degree B appears to be nearer to C.

In normal use, simulator displays offer more information than linear perspective, occlusion and luminance differences, as does the natural world. Reference was made, in the previous chapter, to the different approaches to the study of the way in which the different cues to depth are used. The generalised approaches to the study of optical illusions (Taylor, 1962; Pressey, 1971; Green and Stacey, 1966) each concluded that some form of weighting was applied to the various components within the total flow of information. More recently, attention has been paid to the way in which the various cues are combined: the simple additive model of Bruno and Cutting (1988), the algebraic additive model of Dosher Sperling and Wurst (1986), the relative cue-strength approach of Baird (1992), and the two-stage mathematical approach of Landy and his co-workers (e.g. Landy, Malony, Johnston and Young, 1991). Each approach assumes that any cue to depth will contribute, in some degree, to the overall percept of depth that arises from a specific display.
However, a stronger sense of depth does not necessarily equate with a more accurate perception of spatial layout; earlier reference to art and optical illusions has shown how a powerful impression of depth can be combined with an ambiguous perception of spatial layout, if one cue is in conflict with another. The simple additive model may only apply if all available cues agree as to the general spatial layout: as proposed by Bruno and Cutting (1988), the simple additive model allowed for cues to be negatively weighted, and for the possibility that not all sources of information could be integrated by addition after weighting. Where most cues converge on a single percept of spatial layout, one weak conflicting cue may simply be disregarded (zero weighted, or de-selected); where several weak cues are present, a conflicting cue may not be the weakest, and the processes of selection or weighting must be more complicated. This is acknowledged by the two-stage model of Landy et al (1991) where cues are first evaluated on their own, and then with reference to each other.

In the three experiments now to be described, each stimulus will contain two lines of objects, one varied in length and in object luminance, the other held at constant length and without variation in luminance. On the basis that information from perspective can be separated into different cues (see Chapter 3, section 4.2), the amount of this information will be manipulated as detailed below, while the luminance variation will remain the same from one experiment to the next.
Earlier in this section it was stated that a judgement of the relative spacing of objects in a line said nothing about the length of that line. In this series of experiments, the use of a constant reference line of objects should enable assessment of the effect (whether supporting or conflicting) of the luminance variations (whether from luminance or contrast gradients) on perceived line length. Taking the line of objects A-B-C mentioned above, if the luminance runs from A= highest, receding from the observer to C = lowest, and the background luminance is low, then the luminance gradient cue (following Ames, 1949; Gibson, 1950; or Ittleson, 1960) and the contrast gradient cue (following Ross, 1993; or O'Shea et al, 1993) are not in conflict. If the background luminance is high, however, then the two cues are in conflict. If there are differences in the judged length of the variable line, then the magnitude and direction of those differences should give some indication of the relationship between the amount of perspective information available, and the degree to which luminance or contrast gradient can moderate linear perspective information.

1.2. The information available.

In an earlier chapter, it was pointed out that an artist would consider several different items of depth information as being encompassed by the term 'linear perspective'. Linear perspective is but one of several systems for projecting a section of three-dimensional space onto a two-dimensional surface; its importance (Pirenne, 1970, holding it to be the most important factor in the perception of a flat picture) is that it is viewer-centred, not object centred (Dubery and Willats, 1983). The observer must therefore be at, or near, the correct stationpoint in order to view the projection correctly.
and must also use the available information in the manner intended by the artist or scene
designer. Although based on straight lines, which can themselves stand for a wide
variety of elements in a natural world scene (Kennedy, 1974), the lines in a linear
perspective depiction can enclose areas of differing size, can indicate contours or the
horizon, and thus offer information other than that from the lines alone. To assess the
influence on the overall percept of the scene, by a single information source, it is
necessary to identify the individual components of linear perspective so that manipulation
of both the type and amount of information available can be carried out in a controlled
manner.

Table 4.1 Information manipulations.

<table>
<thead>
<tr>
<th>INFORMATION SOURCE</th>
<th>EXPERIMENT 3</th>
<th>EXPERIMENT 4</th>
<th>EXPERIMENT 5</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminance</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>As Variable</td>
</tr>
<tr>
<td>Contrast</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>As Variable</td>
</tr>
<tr>
<td>Convergence</td>
<td>Yes</td>
<td>Yes</td>
<td>Reduced *</td>
<td>* 2 VP's</td>
</tr>
<tr>
<td>Coincidence</td>
<td>Yes</td>
<td>Reduced *</td>
<td>Yes</td>
<td>* Less Objects</td>
</tr>
<tr>
<td>Depicted size</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Horizon</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>As Variable</td>
</tr>
<tr>
<td>Textured Ground</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Height in Field</td>
<td>Yes</td>
<td>Yes</td>
<td>Reduced *</td>
<td>* Decoupled</td>
</tr>
</tbody>
</table>

Thus, the convergence of parallel lines, normal to the picture plane, to a vanishing point,
can be regarded as a separate item to the number of depicted lines that coincide with a
single line projected from that vanishing point. In Table 4.1, those items of information
that can be separated in this way are set out for each experiment. It can be seen that the amount of information was progressively reduced through the series: Coincidence being reduced for Experiment 4, by reducing the number of objects in the scene, and Convergence, and Height in the Visual Field (HIVF) for Experiment 5, by decoupling the vanishing point for the variable line of objects from that for the comparison line. The exact nature of the reduction in information will be detailed in the appropriate section for each experiment.
2. EXPERIMENT 3

2.1 Introduction.

The first two experiments have shown the stimulus objects in virtual space without any points of reference. In this experiment, the information from linear perspective has been reinforced by the addition of a horizon line in two of the conditions. One condition offers further potential information in the form of ground plane texture. While Computer Generated Images as used in simulators are limited as to the detail that they can display, a horizon line is invariably potentially available, although there may be circumstances when the horizon is not visible to the observer (and hence not displayed) as in the case of an aircraft in a steep climb or dive.

Similarly, despite limitations on the number of polygons that can be displayed on screen, a limited form of ground plane texture is normally present, even if not in the full Gibsonian sense of the term. For the aircraft in a steep dive then, texture without a horizon is possible, but in this instance any change in texture would specify a change in absolute distance, and thus be a dynamic cue. Since all the stimuli in this experiment are static, there will be no condition where there is texture but no horizon. Whilst the scene features referred to above serve as independent cues to depth, they should also generally add to the information available from linear perspective without any conflict. The presence of a horizon line would make information from relative object heights in the visual field available, but such information will not be manipulated here, since the perspective will be of the 'Single Point' form, with a single VP.
Each stimulus used here depicted two parallel lines of identical, equally spaced, objects, with the length (i.e. on the y axis) and the luminance order being varied on one line only. Subjects were required to judge which of the two lines was longer, with a prediction based on the earlier studies that the line in which the object luminance order ran Light-Medium-Dark receding from the observer would be seen as the longest line.

**Unintended luminance variations.**

It had been assumed that the luminance of any polygon on the screen would remain constant at its programmed value at all points within the polygon if this was intended to be so, but this was not the case. The phenomenon of a fall in luminance from screen centre to screen edge was reported by Livingstone and Hubel (1989), but they gave no details of the size of the effect. A series of precise luminance measurements were made to determine the magnitude of this phenomenon, and these will be discussed in a subsequent chapter, as will an experiment to determine the degree to which observers are aware of the reduction. Luminance reduction varies from monitor to monitor, with direction from screen centre, and can exceed 30%. Scene layout for this experiment, and for the others in this chapter, took this reduction into account so as to minimise its influence.

The aim of this experiment was to compare judgements of the perceived length of a line of objects, varied in length and luminance order, with a line of constant length and without any luminance variations. Variation of the amount and type of perspective
information should apply equally to each line of objects, and thus identify any effect from the luminance variations that is influenced by the variation of perspective information.

2.2. Method.

Subjects.

Ten subjects - 6 female, 4 male - took part. They were a mix of undergraduate, and postgraduate students, technical and academic staff from within the Psychology Department of the University of Surrey.

Equipment

The scenes.

These were generated on the BEST and transferred direct to video-tape in the same manner as for experiment 2. Each scene now contained two parallel lines, each of three block objects (see Figure 4.1), 30 high, 15 wide, 10 deep, with the virtual line of view centrally between them, and 5 units above the virtual ground plane. The inter-object spacing was programmed as equal within each line, and the centre objects were at an equal distance from the virtual stationpoint. Hence, variations in depicted object size and separation were derived from their specification within the program. One line - the comparison line - had all objects shaded Medium grey and was held at constant length. The other line - the variable line - carried the shading manipulations (objects shaded to give Light-Medium-Dark Grey or Dark-Medium-Light gradients, and a control
Figure 4.1: typical stimulus as seen by subject.
condition with all objects shaded Medium Grey) and was varied in length. These variations were +/- 1.2% and +/- 3.5% of the length of the comparison line, the choice of their position being constrained by the limits of the BEST co-ordinate system. Three background variations were used: each having a pale grey ‘Sky’, and one of the three following ground planes:

1. Pale grey (matching the ‘sky’, thus giving a plain background without a horizon line) as shown in Figure 4.1.
2. Plain medium red (thus giving a horizon).
3. Medium red-green isoluminant chequer pattern (giving both horizon and texture.

The luminance values (again taken from the video monitor) are shown in Table 4.2 below. As before, the characteristics of the video monitor prevented the values being precisely balanced; however, this has not generally affected the direction or slope of the luminance or contrast gradients.

Table 4.2 Scene luminance values for Experiment 3.

<table>
<thead>
<tr>
<th>SCENE COMPONENT</th>
<th>SCENE</th>
<th>LIGHT</th>
<th>MEDIUM</th>
<th>DARK</th>
<th>SKY</th>
<th>GROUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCENE LIGHT</td>
<td>PLAIN</td>
<td>84</td>
<td>29</td>
<td>12</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>MEDIUM GROUND</td>
<td>HORIZON</td>
<td>95</td>
<td>43</td>
<td>15</td>
<td>170</td>
<td>57</td>
</tr>
<tr>
<td>DARK SKY</td>
<td>TEXTURE</td>
<td>91</td>
<td>39</td>
<td>15</td>
<td>170</td>
<td>57</td>
</tr>
</tbody>
</table>

There were thus three backgrounds and four line lengths for each direction of the luminance gradient and for the control condition. Ten repetitions of each view were pseudo-randomised into the complete experimental sequence; into this sequence were
placed a number of additional views intended to mask the experimental design (these had either unequal spacing between objects or had one line nearer to the viewpoint) and the whole was then cut into four presentation tapes. Each view was preceded by a 3 second red warning screen, was presented for 5 seconds, and was followed by a 3 second black screen (timings accurate to +/- 0.12 seconds). Finally, each tape was cut into four presentation series, each of twenty-four views. An 8-view practice tape was also made.

**Presentation equipment.**

The same Umatic VCR, controller and monitor used in the previous studies were employed here. Subjects were again seated at a table, centrally in front of the monitor, at a distance of 1.8 metres. As with the first two experiments, their head position was not fixed, and a low ambient light level (0.8 lux at the table surface) without any screen reflections was maintained.

**Procedure.**

On being seated, subjects were given a printed set of instructions, a perspective drawing of a typical scene, and a response sheet. For each view, they were required to judge the relative length of the two lines of blocks. For balance, they were randomly assigned to judge which line was longer, or shorter, than the other, with the instructions only differing in this respect. The response sheet had two boxes for each view, arranged in two columns labelled 'Right' and 'Left', and subjects were told to mark the appropriate
box for each view in any manner they wished. The practice series of views was presented, subjects were asked if they had any problems with the task, and the first experimental tape was presented. The four experimental tapes were then shown in random order, with a minimum interval of 20 minutes between any two experimental tapes, so that each subject had four separate sessions. Most subjects undertook one session per day, although two completed the task in two days, and one in three days.

**Design.**

This was a repeated measures design, each subject making ten judgements per view. Judgements for the distracter views were discarded prior to analysis, their layout being such that no use could be made of them. Thus: 10 subjects each made 10 judgements for each of 3 scenes x 4 line lengths x 3 luminance orderings.

**3. Results.**

For each subject, a mean correct score across the ten judgements for each of the three luminance orders, three background scenes and four variable line lengths was calculated. The mean across subjects judgements for the number of times the variable line was judged longer than the comparison line, for each of the three luminance orderings are shown below in Tables 4.3.a,b and c:
Table 4.3.a: Variable line judged longer than comparison line.
(Order L-M-D)

<table>
<thead>
<tr>
<th>LUMINANCE ORDER: LIGHT-MEDIUM-DARK</th>
<th>VARIABLE LINE LENGTH</th>
<th>SCENE</th>
<th>-3.5%</th>
<th>-1.2%</th>
<th>+1.2%</th>
<th>+3.5%</th>
<th>MEAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLAIN</td>
<td>MEAN</td>
<td>2.70</td>
<td>4.00</td>
<td>4.90</td>
<td>7.30</td>
<td>4.72</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1.49</td>
<td>2.26</td>
<td>2.69</td>
<td>1.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HORIZON</td>
<td>MEAN</td>
<td>2.70</td>
<td>4.50</td>
<td>5.30</td>
<td>7.20</td>
<td>4.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1.83</td>
<td>2.80</td>
<td>2.26</td>
<td>1.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEXTURE</td>
<td>MEAN</td>
<td>3.5</td>
<td>4.10</td>
<td>4.40</td>
<td>7.30</td>
<td>4.82</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1.65</td>
<td>2.92</td>
<td>3.10</td>
<td>1.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEAN</td>
<td></td>
<td>2.97</td>
<td>4.20</td>
<td>4.87</td>
<td>7.27</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3.b: Variable line judged longer than comparison line.
(Order D-M-L)

<table>
<thead>
<tr>
<th>LUMINANCE ORDER: DARK-MEDIUM-LIGHT</th>
<th>VARIABLE LINE LENGTH</th>
<th>SCENE</th>
<th>-3.5%</th>
<th>-1.2%</th>
<th>+1.2%</th>
<th>+3.5%</th>
<th>MEAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLAIN</td>
<td>MEAN</td>
<td>2.60</td>
<td>3.80</td>
<td>4.20</td>
<td>5.60</td>
<td>3.85</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1.96</td>
<td>1.99</td>
<td>2.15</td>
<td>1.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HORIZON</td>
<td>MEAN</td>
<td>3.40</td>
<td>2.40</td>
<td>2.40</td>
<td>6.60</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1.43</td>
<td>1.65</td>
<td>1.51</td>
<td>1.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEXTURE</td>
<td>MEAN</td>
<td>4.00</td>
<td>2.10</td>
<td>2.40</td>
<td>5.80</td>
<td>3.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1.70</td>
<td>1.29</td>
<td>1.65</td>
<td>1.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEAN</td>
<td></td>
<td>3.33</td>
<td>2.76</td>
<td>3.00</td>
<td>6.00</td>
<td></td>
<td></td>
</tr>
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Table 4.3.c: Variable line judged longer than comparison line.
(Control)

<table>
<thead>
<tr>
<th>SCENE</th>
<th>VARIABLE LINE LENGTH</th>
<th>MEAN</th>
<th>SD</th>
<th>MEAN</th>
<th>SD</th>
<th>MEAN</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLAIN</td>
<td>-3.5%</td>
<td>1.40</td>
<td>1.35</td>
<td>1.90</td>
<td>1.34</td>
<td>5.20</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>-1.2%</td>
<td>4.70</td>
<td>1.34</td>
<td>4.70</td>
<td>1.34</td>
<td>7.80</td>
<td>1.75</td>
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<td></td>
<td>+1.2%</td>
<td>4.77</td>
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<td>1.34</td>
<td>4.77</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
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<td>5.20</td>
<td>1.75</td>
<td>5.20</td>
<td>1.75</td>
</tr>
<tr>
<td>HORIZON</td>
<td>-3.5%</td>
<td>3.00</td>
<td>1.43</td>
<td>3.00</td>
<td>1.43</td>
<td>8.50</td>
<td>1.27</td>
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<td>2.12</td>
<td>4.40</td>
<td>2.12</td>
<td>8.50</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>+1.2%</td>
<td>8.50</td>
<td>1.27</td>
<td>8.50</td>
<td>1.27</td>
<td>8.50</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>+3.5%</td>
<td>6.10</td>
<td>1.27</td>
<td>6.10</td>
<td>1.27</td>
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<td>1.27</td>
<td>6.10</td>
<td>1.27</td>
</tr>
<tr>
<td>TEXTURE</td>
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<td>1.34</td>
<td>1.30</td>
<td>1.34</td>
<td>6.30</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>-1.2%</td>
<td>4.40</td>
<td>1.43</td>
<td>4.40</td>
<td>1.43</td>
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<td>2.49</td>
</tr>
<tr>
<td></td>
<td>+1.2%</td>
<td>6.30</td>
<td>1.83</td>
<td>6.30</td>
<td>1.83</td>
<td>6.30</td>
<td>1.83</td>
</tr>
<tr>
<td></td>
<td>+3.5%</td>
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<td>5.00</td>
<td>2.49</td>
<td>5.00</td>
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<tr>
<td>MEAN</td>
<td>-3.5%</td>
<td>1.90</td>
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<td>6.50</td>
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<td>2.71</td>
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<td>2.71</td>
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<td></td>
<td>+3.5%</td>
<td>8.10</td>
<td>2.71</td>
<td>8.10</td>
<td>2.71</td>
<td>8.10</td>
<td>2.71</td>
</tr>
</tbody>
</table>

Analysis of variance on the mean subject scores for judgements of the variable line as longer than the constant line, on the conditions of luminance order, line length, and scene type, shows the following:

Main Effects:
- Luminance Order df 2,18 F=7.13 p = .005
- Scene df 2,18 F=6.71 p = .008
- Line Length df 3,27 F=31.31 p = < .001

Interactions:
- Order by Scene df 4,36 F=4.56 p = .004
- Order by Length df 6,54 F=6.74 p = < .001
- Scene by Length df 6,54 F=2.71 p = .022
- Order by Scene by Length df 12,108 F=2.71 p = < .001

Thus, all of the main effects and interactions are significant. Reference to Tables 4.3.a, b and c, above, will show that there is much less difference, in the across-subject means for the variable line being judged as longer than the comparison line, between any of the
background scenes in the Light-Medium-Dark condition, than for the other two conditions. The Dark-Medium-Light condition shows a consistent tendency to judge the variable line as shorter than the comparison line.

Figure 4.2 illustrates the Luminance Order by Line Length interaction. It can be seen that the line for the control condition passes almost directly through the intersection between 50% judgement and zero length difference, while the lines for the other two conditions do not cross the 50% judgement line until the variable line length is longer than the comparison line. Post hoc comparisons (Newman Keuls) between the across-subject means, collapsed across background scene, for each combination of luminance orderings, show that the difference between the luminance orders L-M-D and D-M-L, and between Medium and D-M-L are significant at the P<0.05 level, but that between L-M-D and Medium is not significant. Comparisons between successive pairs of variable line lengths show that the differences between the -1.2% and +1.2% line lengths are significant at the P<0.05 level, and between the +1.2% and +3.5% line lengths are significant at the P<0.01 level.

These results suggest that the luminance order D-M-L can be considered as compressing the perceived length of the variable line as compared to the other two luminance orderings.
Figure 4.2: Interaction: line length and luminance order.
Figure 4.3: Interaction: line length and background scene.
Figure 4.3 illustrates the Background Scene by Line Length interaction. It can be seen that addition of a horizon line leads to substantially less compression of the variable line length than either of the other two conditions. The horizon line with textured ground plane is more compressed than the horizon alone, but it is only at the +1.2% variable line length that there is a major difference between judgements for these two conditions. Comparisons between the across-subject means, collapsed across luminance order, for each combination of the three background scene conditions are significant at the P < 0.01 level. Comparisons between successive pairs of variable line lengths again show that the differences between the -1.2% and +1.2% line lengths are significant at the P < 0.05 level, and between the +1.2% and +3.5% line lengths are significant at the P < 0.01 level.

Figure 4.4 illustrates the interaction of luminance order and background scene. It can be seen that the order L-M-D is close to 50% judgement of the variable line being longer than the comparison line, while the order D-M-L is judged as being substantially shorter. The combination of all objects being shaded Medium and the plain background shows the shortest judgements of variable line length; the combination of all Medium objects and a horizon line shows the longest judgements of variable line length. Comparisons between the across-subject means, collapsed across lengths of the variable line, for each combination of the three background scene conditions are significant at the P < 0.01 level, and for each combination of luminance orderings again show that the difference between the luminance orders L-M-D and D-M-L, and between Medium and
Figure 4.4: Interaction: Luminance order and background scene.
D-M-L are significant at the $P < 0.05$ level, but that between L-M-D and Medium is not significant.

Thus, for the interactions involving variable line length, the step between the -3.5% and -1.2% line lengths is not significant, as is the case with the difference between the L-M-D and all-Medium luminance orders. It can also be said that the addition of texture to the ground plane has generally acted to reduce the perceived length of the variable line.

The differences in compression effects are taken to account for the three way interaction. It can be seen that it is only in the D-M-L condition that the scene has a marked effect, and then only when a horizon line - with or without a textured ground plane - is present. It is these two cases - D-M-L ordering, with some form of horizon present - that show the lowest percentage judgements of the variable line being longer than the comparison line at the -1.2% line length, and the greatest percentage at the +1.2% length. This would suggest that the D-M-L ordering is acting to compress the perceived length of the line, so that when the variable line length is actually just shorter than the comparison line, the compression supports the other information; when the variable line is just longer, the D-M-L order conflicts with the other information and produces inappropriate judgements.
2.4. Discussion.

The results show the L-M-D Luminance Order generally producing a longer judgement of line length than does the order D-M-L. The mean judgements for the luminance order L-M-D are more accurate than for the order D-M-L; this is also the case when the different background scenes are considered, except for those scenes with a textureless ground plane where the means are the same. The effects of Line Length are not consistent between conditions, but in general, the variable line is judged to be the shorter until it is nearly 2% longer than the reference line.

These results suggest that the direction of luminance gradient has influenced the compression effect on judgements of line length, and, as predicted, the luminance order Light-Medium-Dark has resulted in longer judgements of variable line length than the order D-M-L. However, the comparison line also has both luminance and contrast gradients; these are zero in each case, as are the luminance and contrast gradients in the control condition. Figures 4.2 and 4.4, and the associated post hoc comparisons indicate that statistical significance in this experiment is not simply a matter of zero gradient versus a directional gradient.

The two previous studies had suggested that the effect of differences in luminance had been to make the object with the highest luminance appear nearer. In this experiment, the centre object in each line was of equal luminance and was of equal distance from the stationpoint and hence from the observer. With the luminance order L-M-D, the front object may well have appeared to be nearer to an observer than the front object in the
comparison line, and this alone would account for the variable line being seen as longer than the comparison line when the variable line was in fact shorter. To extend this to suggesting that the dark rear object in the variable line would appear further away than the rear object in the comparison line, would require that the effect of luminance differences has had a major influence on the information from perspective. Clearly, this has not happened for every combination of variable line length and background scene. Reference to Figure 4.4 does show that the negative luminance gradient of the order L-M-D order has consistently led to longer judgements of variable line length than the negative contrast gradient D-M-L. However, Figure 4.4 also shows a strong influence from the type of background scene: it can be seen that the additional information from the horizon line - and to a lesser degree from the ground plane texture - has least influenced the judgements concerning the L-M-D ordering. The type of background scene has had the greatest influence on the judgements concerning the variable line with zero contrast and luminance gradients; while there is no significant difference between the means, across subjects and across variable line lengths, for the all-Medium and L-M-D luminance orders, judgements of the all-Medium variable line as longer than the comparison line do, in fact, double with the addition of a horizon line, and then reduce with the further addition of ground plane texture. This suggests that any effect from the luminance or contrast gradient offered by a line of objects may depend on the amount and type of other information available; that the addition of ground plane texture has shown a reduction in the number of 'longer than' judgements argues that additional information does not always improve the perception of spatial layout.
O'Shea et al (1994) argue that the object having the greatest contrast with its background will be seen as nearer, yet here the reverse appears to be true. The contrast increases as the objects get darker and following O'Shea one would expect the L-M-D line to be compressed more than the reverse. However, O'Shea's stimuli offered only luminance information (foreground and background luminance, and thus the contrast between them), and it can be seen here that additional information has produced a complex effect. Thus, the direction of the luminance gradient, rather than the direction of the contrast gradient, would appear to be more influential in the present experiment, but as a moderator of, or moderated by, the other information available, rather than as a primary information source.

In this experiment, each line of objects has a luminance gradient, and because the background is constant there is also a contrast gradient. The contrast gradient is flat for the comparison line and for the all-Medium variable line, but the slope reverses for the other two luminance orders of the variable line. To the observer then, any compression due to the contrast gradient (which here reduces with distance) of the Dark-to-Light order may well appear natural, since it is similar to the natural world contrast reduction over distance due to aerial perspective. This would not exclude the luminance order L-M-D from giving rise to longer judgements of line length than the D-M-L order, but does not account for the D-M-L line being judged longer more often than the other two luminance orders at the -3.5 variable line length.
2.5 Conclusion.

This experiment confirms the view that luminance information, in the form of a luminance gradient or a contrast gradient, can moderate that from simple linear perspective, with the degree of moderation being influenced by the amount of other information present. For the next experiment, the amount of information from linear perspective will be reduced, and the control condition (where all objects had the same luminance) removed: the objective being a clearer understanding of the relationship between positive or negative luminance gradients and contrast gradients, and the other information available, on perceptions of spatial layout.
3. EXPERIMENT 4

3.1. Introduction.

The preceding experiment gave further support for the argument that differences in luminance between objects in a scene will affect judgements of their relative position. The scenes remained simple in content, but, in containing two lines of three objects, it can be said that the amount of information from linear perspective was increased: for each line, three edges or three points fitted each line radiating from the VP. A horizon line, both with and without ground plane texture, was present; thus, the changes in displayed object height due to perspective scaling, offered additional depth information from the changes in the position of the top and bottom edges relative to the horizon.

The results suggested that the luminance ordering (or gradient) of Light-Medium-Dark, receding from the observer, had generally led to more judgements of the variable line being longer than the comparison line than had the order Dark-Medium-Light, and thus that the luminance order Dark-Medium-Light had led to an apparent compression of the variable line relative to the Light-Medium-Dark order. This is taken to support the views of Ames, (1949), Gibson, (1966), Ittelson, (1966) and Baird (1992), where a decrease in luminance is equated with an increase in distance, rather than the views of Ross, (1967, 1993); Farné, (1977); and O'Shea et al, (1994); who would equate a reduction in contrast with an increase in distance. All three preceding experiments have assumed the correctness of Pirenne's (1972) argument that the primary source of information on spatial layout has been linear perspective; if this is so, then a reduction
in the information from perspective should permit either luminance or contrast information, or both, to have a greater influence on judgements of spatial layout. However, the preceding experiment also indicated that the effect of the luminance order was to some degree dependent on the amount of other information available.

For the present experiment, the amount, but not the type of information from perspective was reduced by removing the centre object from each line. The projections of lines drawn through the object apices and parallel edges in the z plane still met at a single VP, but only two points or two edges now fitted a line from the VP. Since the majority of interactions occurred when the difference between comparison and variable line lengths exceeded 1.2%, the range of variable line lengths was extended. The effect of the ground plane texture had been marked only for the D-M-L luminance order, so this condition was omitted to simplify an assessment of the luminance and contrast order effects. Removing the medium shaded object from the centre of each line did not alter the direction or slope of the luminance and contrast gradients, although the Light-Dark or Dark-Light ordering could be seen as a reduction in this information.

The aim of this experiment was to determine the effects obtained when the information from linear perspective and object luminance was reduced, and the range of variable line lengths was increased.
3.2. Method.

The method generally followed that for Experiment 3, only the differences will be given here.

Subjects.

Ten subjects - 6 female, 4 male - took part. They were all first-year undergraduate students in their first term in the Psychology Department of the University of Surrey.

Equipment

The scenes.

These were generated on the BEST and transferred direct to video-tape in the same manner as for Experiment 3. The centre object was removed from each line so that each scene now contained two pairs of objects. Since the addition of ground plane texture seemed not to be beneficial, the texture was omitted. The line length variations were now +/- 1.2%, +/- 3.5% and +/-7% of the length of the comparison line. There were thus two backgrounds and six line lengths for each direction of the luminance gradient. No additional distracter views were used.

Design.

This was a repeated measures design, each subject making ten judgements per view of
whether the variable line was longer or shorter than the comparison line. Thus: 10 subjects each made 10 judgements for each of 2 background scenes x 6 line lengths x 2 luminance orderings.

3.3. Results.

For each subject, a mean score across the ten judgements for each of the two luminance orders, three background scenes and six variable line lengths was calculated. The mean judgements across subjects, for the variable line being seen as longer than the comparison line, are shown below in Table 4.4.

<table>
<thead>
<tr>
<th>ORDER</th>
<th>-7%</th>
<th>-3.5%</th>
<th>-1.2%</th>
<th>+1.2%</th>
<th>+3.5%</th>
<th>+7%</th>
<th>MEAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-D HORIZON</td>
<td>Mean</td>
<td>4.10</td>
<td>4.70</td>
<td>3.60</td>
<td>7.10</td>
<td>6.00</td>
<td>4.40</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>2.02</td>
<td>2.00</td>
<td>1.26</td>
<td>1.79</td>
<td>1.89</td>
<td>3.5</td>
</tr>
<tr>
<td>L-D</td>
<td>Mean</td>
<td>4.00</td>
<td>4.50</td>
<td>4.60</td>
<td>6.80</td>
<td>6.40</td>
<td>4.80</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>2.26</td>
<td>2.12</td>
<td>1.17</td>
<td>2.15</td>
<td>1.35</td>
<td>3.43</td>
</tr>
<tr>
<td>D-L HORIZON</td>
<td>Mean</td>
<td>3.60</td>
<td>4.70</td>
<td>5.10</td>
<td>6.50</td>
<td>6.40</td>
<td>4.20</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>2.27</td>
<td>2.26</td>
<td>1.37</td>
<td>2.32</td>
<td>2.07</td>
<td>3.19</td>
</tr>
<tr>
<td>D-L</td>
<td>Mean</td>
<td>4.00</td>
<td>4.00</td>
<td>5.10</td>
<td>6.30</td>
<td>6.20</td>
<td>5.00</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>2.62</td>
<td>2.05</td>
<td>1.91</td>
<td>1.89</td>
<td>1.93</td>
<td>2.71</td>
</tr>
<tr>
<td>MEANS</td>
<td></td>
<td>3.92</td>
<td>4.47</td>
<td>4.60</td>
<td>6.67</td>
<td>6.25</td>
<td>4.60</td>
</tr>
</tbody>
</table>

Analysis of variance on the mean subject scores for correct judgements on the factors of Luminance Order, Line Length, and Scene type, shows the following:
Main Effects:

- Luminance Order: df 1,9, F = 0.01, p = .973
- Background Scene: df 1,9, F = 0.17, p = .693
- Line Length: df 5,45, F = 3.19, p = .015

Interactions:

- Order by Scene: df 1,9, F = 1.58, p = .612
- Order by Length: df 5,45, F = 1.60, p = .180
- Scene by Length: df 5,45, F = 0.88, p = .502

Three way interaction:

- Order by Scene by Length: df 5,45, F = 0.36, p = .874

Thus, of the main effects, only the variable line length was significant, and none of the interactions were significant.

Examination of the means in Table 4.3 show a general tendency for the number of judgements that the variable line is longer than the comparison line to increase from a variable line length of -7% to +1.2%, but to decrease from +1.2% to +7%. To enable a direct comparison with the results of Experiment 3, the analysis of variance was repeated, after excluding the -7% and +7% variable line lengths. This gave the following results:
Main Effects:

<table>
<thead>
<tr>
<th>Factor</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminance Order</td>
<td>1,9</td>
<td>0.18</td>
<td>0.680</td>
</tr>
<tr>
<td>Background Scene</td>
<td>1,9</td>
<td>0.01</td>
<td>0.927</td>
</tr>
<tr>
<td>Line Length</td>
<td>3,27</td>
<td>4.74</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Interactions:

<table>
<thead>
<tr>
<th>Interaction</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order by Scene</td>
<td>1,9</td>
<td>1.71</td>
<td>0.223</td>
</tr>
<tr>
<td>Order by Length</td>
<td>3,27</td>
<td>3.47</td>
<td>0.030</td>
</tr>
<tr>
<td>Scene by Length</td>
<td>3,27</td>
<td>0.91</td>
<td>0.449</td>
</tr>
</tbody>
</table>

Three way interaction:

<table>
<thead>
<tr>
<th>Interaction</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order by Scene by Length</td>
<td>3,27</td>
<td>0.24</td>
<td>0.867</td>
</tr>
</tbody>
</table>

The interaction of luminance order and length is shown in Figure 4.5, where it can be seen that the L-D luminance order produces less judgements of the variable line being longer than the comparison line at the -1.2% variable line length than does the D-L luminance order, but more judgements at the +1.2 variable line length. In post hoc comparisons (Newman Keuls) between the two luminance orders, and between adjacent lengths of the variable line, there were no significant difference between the means. This would suggest that reducing the amount of information available has effectively eliminated any effect from the luminance variations.

Transforming the scores to show the number of correct judgements revealed a further aspect of the effect of reducing the amount of perspective information. The overall mean judgement was slightly better than could be expected to obtain by chance (59.6% correct) yet one subject scored 83.75% correct judgements. Two subjects scored worse than chance with 45.84% and 46.25%. The highest scoring subject had also taken the Shapes Analysis Test (Heim, Watts and Simmonds, 1972) as part of a test battery.
Figure 4.5: Interaction: luminance order and line length.
administered to volunteer 1st Year undergraduates, and had produced the highest score in that test. Since the Shapes Analysis Test is one of subjects' ability to extract 2D and 3D shapes from line drawings, it seemed plausible that scores on that test may well relate to subjects' ability to 'see' linear perspective. Seven subjects in the present experiment had taken the Shapes Analysis Test, and, when the scores were correlated with the means by subject for correct judgements in this experiment, a correlation of 0.59 (p = .054) was obtained.

3.4. Discussion.

The results show that when the information from linear perspective is reduced, the effect of any variation in object luminance is non-significant. Even when the data from the longest and shortest variable line length is set aside, only the interaction between luminance order and variable line length is significant.

The results of the previous studies supported the view that the effect of an increase in luminance had been to make the brighter object appear nearer; here, there is no support for this, or for the argument that greater contrast is equated with an object being nearer. With only two objects in each line, the slope and direction of the luminance and contrast gradients were unaltered from the preceding experiment. If brighter objects were to appear nearer than darker objects, one would expect the Light-Dark line to be judged as longer than the Dark-Light line. In this experiment, the Light-Dark line has been
judged longer than the Dark-Light line when there is no horizon available, but shorter when a horizon is present.

In the scenes without a horizon, this experiment is analogous to that of O'Shea et al (1994); that no significant effects are attributable to the luminance ordering could suggest that information from linear perspective has been far stronger than that from luminance or contrast. Following O'Shea et al (1994) one would expect the Light-to-Dark line to be judged as shorter than the reverse, and there are some combinations of variable line length and background scene where this does occur. Thus, when the total information is reduced by removing the centre object from each line, contrast per se rather than luminance per se appears to have had some influence on the judgements of variable line length. One possible explanation is that contrast became the primary source of information.

Each line (or pair) of objects offered a luminance gradient and a contrast gradient (flat for the comparison line, with the slope reversing between the two luminance orders of the variable line). One alternative explanation of the results above is that the information from contrast (to follow O'Shea et al, 1994) was of sufficient strength as to provide the primary information on spatial layout. In this event, the dark object - having the greater contrast - would be seen as nearer regardless of the information from perspective, and an invalid luminance gradient would still be able to function as a moderator. This, in turn, would imply that information from linear perspective had not
been used; the means shown in Table 4.4 argue that this could not have occurred on a consistent basis.

3.5. Conclusion.

This experiment provides only limited further support for holding the view that luminance information can moderate that from simple linear perspective. Reducing the amount of information from linear perspective has seen mean judgements that are little better than chance. As with Experiment 3, it would appear that any effect from luminance variations does depend on the total amount of information available.
4. EXPERIMENT 5

4.1. Introduction.

The effects obtained in Experiment 4 were contrary to those in the first three experiments. With the reduction in the number of objects in a line, the previous tendency for a line with a luminance gradient running high to low from the observer to be seen as longer than a line with the opposite gradient, was reversed. As noted in Chapter 3, luminance differences can offer information from both luminance gradients and contrast gradients, each potentially able to moderate the information from perspective. Thus, three objects in a line gave adequate information for the spatial layout of each scene to be perceived as designed, with perspective moderated by luminance or luminance gradient; two objects in a line did not give adequate information, and either contrast or contrast gradient became the moderator, (Ross, 1993, O'Shea et al, 1994) or possibly the prime source of information, (Rohally and Wilson, 1993). The presence or absence of a horizon line did not appear to have played any significant role in the judgements.

Height in the visual field (HIVF) is generally regarded as an important source of depth information (Ittleson, 1966; Bruce and Green, 1985). This is normally referred to in terms of an object seeming to rise toward the horizon as its distance from the observer increases, but as has been pointed out in an earlier chapter, an object above the horizon will get lower in the visual field -thus falling toward the horizon - with increasing
distance. Normally, the HIVF information would specify a spatial layout similar to that specified by perspective. In the four previous experiments, HIVF has been correlated with the other information from linear perspective, here the HIVF information will be de-coupled from the other perspective information; returning to lines of three objects will restore the information from the depicted size of the objects in each line to that available in Experiment 3.

In this experiment, the method chosen was to alter the vertical location of the objects in the variable line. The objects in the variable length line were set so that the vanishing point for the projection of lines through their edges and apices was higher or lower in the visual plane than that for the comparison line, and thus above or below the horizon line when such a line was present.

The variable line was therefore inclined upward with increasing distance from the observer, or downward. One effect of this manipulation was that the centre, and either the front or rear object in the variable line was wholly above the horizon line. Thus, while each line contained three objects as did the lines in Experiment 3, and had the same density of contrast or luminance gradient, perspective dictated a separate vanishing point for each line. Each line still offered Single Point perspective, but the VP’s were separated vertically.
The last experiment did suggest that contrast may have led to the variable line having been perceived as reversed in layout. Separation of the vanishing points, as described above, would not alter the task of assessing the length of the comparison line, since the luminance or contrast gradient would still be flat; judgements of the variable line would be more difficult, due to the manipulation of object height relative to the horizon, thus offering scope for the luminance orderings to have a somewhat greater influence. In the light of the previous experiment, subjects were, where possible, selected to represent a normal distribution of scores on the Shapes Analysis Test.

The primary aim of this experiment was to determine the influence of object luminance differences, when the information from the convergence component of linear perspective was reduced, and the vanishing point for the variable line was decoupled from that for the comparison line, by adjustments to the HIVF information from the variable line. A secondary aim was to investigate the possibility of individual differences affecting depth perception.

4.2. Method.

Since this generally follows that for Experiments 3 and 4, only the differences will be given here.
Subjects.

Thirteen subjects - 11 female, 2 male - took part. They were all first-year undergraduate students in the Psychology Department of the University of Surrey. Eleven were selected on the basis of their scores on the Shapes Analysis Test so as to give a broad distribution of scores on that test. The remaining two were Overseas Exchange students fulfilling a course requirement.

Equipment.

The scenes.

The centre object was replaced in each line so that each scene reverted to two lines, each of three objects. The line length variations used were +/- 3.5% and +/-7% of the length of the comparison line. The objects in the variable line were adjusted so that the centre object was elevated 5 units above the ground plane, and the front or rear objects were elevated 10 units. For any combination of line length and luminance order, five views were provided for each inclination of the line in the interests of balance. The two backgrounds from the previous experiment were retained.

Design.

This was again a repeated measures design, each subject making ten judgements per view. Thus: 13 subjects each made 10 judgements for each of 2 background scenes x 2 directions of inclination x 4 line lengths x 2 luminance orderings.
4.3. Results.

For each subject, a mean score for the number of times that the variable line was judged as longer than the comparison line, across the ten judgements for each of the two luminance orders, two background scenes, two inclinations and four variable line lengths, was calculated. These mean judgements across subjects are shown below in Table 4.5.

Table 4.5: Mean judgements: variable line longer than comparison line.

<table>
<thead>
<tr>
<th>INCLINATION OF VARIABLE LINE</th>
<th>SCENE/ORDER</th>
<th>MEAN JUDGEMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Variable line length relative to comparison line.</td>
</tr>
<tr>
<td>LINE ASCENDS WITH DISTANCE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-M-D</td>
<td>S.D.</td>
<td>3.20</td>
</tr>
<tr>
<td>L-M-D + HORIZON</td>
<td>MEAN</td>
<td>5.92</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>3.45</td>
</tr>
<tr>
<td>D-M-L</td>
<td>MEAN</td>
<td>6.92</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>8.12</td>
</tr>
<tr>
<td>D-M-L + HORIZON</td>
<td>MEAN</td>
<td>6.38</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>2.96</td>
</tr>
<tr>
<td>MEANS</td>
<td></td>
<td>6.13</td>
</tr>
<tr>
<td>LINE DESCENDS WITH DISTANCE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-M-D</td>
<td>S.D.</td>
<td>3.53</td>
</tr>
<tr>
<td>L-M-D + HORIZON</td>
<td>MEAN</td>
<td>5.77</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>3.53</td>
</tr>
<tr>
<td>D-M-L</td>
<td>MEAN</td>
<td>6.38</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>3.20</td>
</tr>
<tr>
<td>D-M-L + HORIZON</td>
<td>MEAN</td>
<td>6.00</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td>3.49</td>
</tr>
<tr>
<td>MEANS</td>
<td></td>
<td>5.75</td>
</tr>
</tbody>
</table>
Analysis of variance on the mean subject scores for correct judgements on the factors of Line Inclination, Luminance Order, Background Scene and Line Length shows the following:

Main Effects:

<table>
<thead>
<tr>
<th>Factor</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination</td>
<td>1,12</td>
<td>53.05</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Luminance Order</td>
<td>1,12</td>
<td>46.67</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Background Scene</td>
<td>1,12</td>
<td>108.13</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Line Length</td>
<td>3,36</td>
<td>3.69</td>
<td>.020</td>
</tr>
</tbody>
</table>

Interactions:

Two-way:

<table>
<thead>
<tr>
<th>Interaction</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination by Luminance Order</td>
<td>1,12</td>
<td>238.26</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Inclination by Scene</td>
<td>1,12</td>
<td>251.37</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Inclination by line Length</td>
<td>3,36</td>
<td>6.88</td>
<td>.001</td>
</tr>
<tr>
<td>Luminance Order by Scene</td>
<td>1,12</td>
<td>190.68</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Luminance Order by Length</td>
<td>3,36</td>
<td>26.90</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Scene by Line Length</td>
<td>3,36</td>
<td>30.57</td>
<td>&lt; .001</td>
</tr>
</tbody>
</table>

Three-way:

<table>
<thead>
<tr>
<th>Interaction</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination by Lum. Order by Scene</td>
<td>1,12</td>
<td>222.32</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Inclination by Lum. Order by Length</td>
<td>3,36</td>
<td>11.36</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Inclination by Scene by Length</td>
<td>3,36</td>
<td>10.25</td>
<td>&lt; .001</td>
</tr>
<tr>
<td>Lum. Order by Length by Scene</td>
<td>3,36</td>
<td>27.68</td>
<td>&lt; .001</td>
</tr>
</tbody>
</table>

Four-way:

<table>
<thead>
<tr>
<th>Interaction</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lum. Order by Length by Scene by Inclination</td>
<td>3,33</td>
<td>27.86</td>
<td>&lt; .001</td>
</tr>
</tbody>
</table>

Thus, all main effects and interactions are significant. In general, the variable line has been judged as longer than the comparison line; the only exception being the luminance order L-M-D when the scene has no horizon, and the objects in the variable line descend with increasing distance. The luminance order L-M-D is consistently judged as shorter than the order D-M-L at the two shorter variable line lengths.
Figure 4.6: Interaction: luminance order and variable line inclination.
Two way interactions:

The interaction between the luminance order and the inclination of the variable line of objects is shown in Figure 4.6, where the data are collapsed over variable line length and type of background scene. It can be seen that the luminance order D-M-L shows no effective change in the percentage of judgments that the variable line is longer than the reference line, from one line inclination to the other (the variable line descending with distance shows 0.1% more judgments); while the luminance order L-M-D shows a drop in judgments that the variable line is longer than the comparison line of 0.9% from the variable line ascending with distance, to when it descends with distance. The luminance order L-M-D is consistently judged as shorter than the order D-M-L. Post-hoc comparisons (Newman-Keuls) between the two levels of luminance order, and the two levels of variable line inclination, are not significant.

Figure 4.7 shows the interaction between the background scene and the inclination of the variable line. For either type of background, the percentage of judgments that the variable line is longer than the comparison line is greater when the variable line ascends with distance from the observer. There are more such judgments when a horizon is present, and the difference between the two types of background scene is less when the variable line descends with distance than when it ascends with distance. Post-hoc comparisons (Newman-Keuls) between the two levels of background scene, and the two levels of variable line inclination, are not significant.
Figure 4.7: Interaction: background scene and variable line inclination.
Figure 4.8: Interaction: line length and line inclination.
Figure 4.8 shows the inclination by line length interaction. Overall, when the variable line ascends with distance from the observer, it is judged longer than when it descends with distance, by 1.4%. The variable line ascending with distance is also influenced more by the length of the variable line, and it will be seen that at variable line lengths of -3.5% and +7% of the reference line, the ascending line is judged as being very slightly shorter than the descending line. Post-hoc comparisons between the two levels of variable line inclination, are not significant, nor are comparisons between the -7% and -3.5%, or the +3.5% and +7% variable line lengths; that between the -3.5% and +3.5% is significant at the p > 0.01 level.

The luminance order by background scene interaction is shown in figure 4.9. It can be seen that the luminance order D-M-L is judged to be longer than the order L-M-D, and that the difference between the two levels of this factor is slightly less when a horizon is present in the background scene. The differences between the two levels of either factor are not significant.

Figure 4.10 shows the interaction between luminance order and variable line length. The luminance order D-M-L is judged to be substantially longer than the order L-M-D at the shorter variable line lengths, is only just longer at the +3.5% longer line length, and at the +7% variable line length, the luminance order is judged to be longer. As with the interaction between inclination and line length, comparisons between the -7%
Figure 4.9: Interaction: Luminance order and background scene.
Figure 4.10: Interaction: Luminance order and line length.
and -3.5%, and the +3.5% and +7% variable line lengths are not significant; that between the -3.5% and +3.5% variable line lengths is significant at the $p<0.01$ level, and the difference between the two levels of luminance order is significant at the $p<0.05$ level.

Figure 4.11 shows the scene by line length interaction. The presence of a horizon line leads to more judgements that the variable line is longer than the reference line. As with the inclination and line length interaction, post-hoc comparisons between the two levels of background scene are not significant, nor are comparisons between the -7% and -3.5%, or the +3.5% and +7% variable line lengths; that between the +3.5% and +3.5% is significant at the $p>0.01$ level.

Three way interactions:
The interaction of luminance order, background scene and line length is shown in Figure 4.12. When the variable line ascends with distance from the observer, the increase in judgements that the variable line is longer than the comparison line when the luminance order changes from L-M-D to D-M-L, is much greater when there is no horizon in the background scene. When the variable line descends with distance from the observer, the increase in judgements that the variable line is longer than the comparison line when the luminance order changes from L-M-D to D-M-L, is now greater when there is a horizon on the background scene. Post-hoc comparisons show a significant difference in the
Figure 4.11: Interaction: background scene and line length.

Length of variable line compared to comparison line.

% of judgements that variable line is longer than comparison line.

COLLAPSED OVER VARIABLE LINE INCLINATION AND LUMINANCE ORDER

NO HORIZON

HORIZON
Figure 4.12: Interaction: luminance order, background scene and line length.
means (at the p<0.05 level) between the two luminance orders when the variable line ascends with distance, but no other comparisons are significant.

Figure 4.13 shows the interaction between luminance order, variable line length and variable line inclination. The luminance order D-M-L has the highest percentage of judgements that the variable line is longer than the comparison line length is 7% shorter than the comparison line, but the lowest percentage of such judgements when the variable line length is 7% longer than the comparison line. The two levels of the luminance order L-M-D are effectively the same (they diverge only slightly as the length of the variable line increases); however, the two levels of the luminance order D-M-L show a marked divergence at the two extremes of variable line length. Post-hoc comparisons show significant differences between the means for the two levels of luminance order at the -3.5% variable line length (at the p<0.05 level) and between the -3.5% and +3.5% variable line lengths.

Figure 4.14 shows the interaction between variable line length, line inclination and background scene. It can be seen that for the two levels of background scene without a horizon, the line for the descending variable line is effectively straight, while that for the ascending line falls between the -7% and -3.5% variable line lengths, is steeper between -3.5% and +3.5%, and climbs only slightly to +7% line length. The differences between the means of the two levels of variable line inclination, and between the means of the two levels of background scene are not significant, the difference
Figure 4.13: Interaction: luminance order, line length and inclination.
Figure 4.14: Interaction: line length, inclination and background scene.
Figure 4.15: Interaction: line length, luminance order and background scene.
between the means for the -3.5% and +3.5% variable line lengths is significant at the p > 0.01 level.

Figure 4.15 shows the interaction between luminance order, variable line length and background scene. The line for the luminance order D-M-L, without a horizon available, shows the least change with variations in the variable line length, whereas the equivalent line for the order L-M-D shows the greatest change with variations in the variable line length. The point at which these two lines intersect occurs before the variable line length is 3.5% longer than the comparison line; in Figure 4.10, with the effect of the two levels of background scene taken out, the intersection occurred after the variable line length exceeded the comparison line length by 3.5%. Judgements that the variable line is longer than the comparison line converge, as the variable line length increases, for the two levels of background scene for the luminance order L-M-D. Comparisons between the means of the two levels of luminance order, and between the means of the two levels of background scene, are not significant; again, the difference between the means for the -3.5% and +3.5% levels of variable line length is significant at the p < 0.01 level.

Since the secondary aim of this experiment was to look at the possible effects of individual differences on depth perception, the scores on the Shapes Analysis Test for each of the eleven subjects for whom it was available, were compared with their mean correct score across all conditions in this experiment. With an overall mean score of
6.36 (63.6% correct judgements), subjects' performance in this experiment was improved over the previous one (overall mean of 58.85%), yet two subjects were just below the chance level (each with 49.4%) and one exactly on chance. The Shapes Analysis Test gives as a total score, the product of the scores on 2-D and 3-D stimuli. The Pearson Product Moment Correlations obtained when the Shapes Analysis Test scores were correlated with the means by subject for correct judgements in this experiment were:

<table>
<thead>
<tr>
<th>Shapes Analysis Test</th>
<th>df = 9</th>
<th>r</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td></td>
<td>0.7536</td>
<td>.004</td>
</tr>
<tr>
<td>2-D</td>
<td></td>
<td>0.7078</td>
<td>.007</td>
</tr>
<tr>
<td>3-D</td>
<td></td>
<td>0.7078</td>
<td>.007</td>
</tr>
</tbody>
</table>

This argues that such individual differences as are measured by the Shapes Analysis Test are also present in the perception of spatial layout in scenes presented on the flat screen of a monitor, the individual differences accounting for half the variance.

For balance, subjects had been randomly assigned to one of two groups: one group instructed to judge which line was shorter, and the other to judge which line was longer. It will be recalled from Table 4.6 that in only one instance was the mean judgement such that the variable line was judged to be shorter than the comparison line. The mean judgements for the remaining fifteen conditions where the variable line was shorter than the comparison line were, therefore, incorrect. The mean scores for each subject were transformed into scores for correct judgements (with a maximum value of 10), and were then collapsed down to means across luminance order, variable line length and background scene, so as to give two scores: for variable lines ascending over distance,
and for variable lines descending over distance. This enabled the use of t-tests (2-tailed) between groups for each condition.

"Judge which line is longest" = Group 1
"Judge which line is shortest" = Group 2

Test for variable line ascending with distance:

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>S.D.</th>
<th>df</th>
<th>F ratio</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>7</td>
<td>5.74</td>
<td>.774</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 2</td>
<td>6</td>
<td>6.89</td>
<td>.842</td>
<td>11</td>
<td>1.18</td>
<td>-2.58</td>
<td>.026</td>
</tr>
</tbody>
</table>

Test for variable line descending with distance:

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>S.D.</th>
<th>df</th>
<th>F ratio</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>7</td>
<td>5.62</td>
<td>.718</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 2</td>
<td>6</td>
<td>7.23</td>
<td>1.42</td>
<td>11</td>
<td>2.89</td>
<td>-2.65</td>
<td>.023</td>
</tr>
</tbody>
</table>

It can be seen that the mean scores for accuracy of judgement are significantly higher for those subjects instructed to judge which line was shorter.

4.4. Discussion.

The results show that the variations in luminance order have again influenced judgements of spatial layout. The effect is stronger when the variable line is shorter than the comparison line, with a general tendency to judge the variable line as longer than the comparison line at both -7% and -3.5% line lengths. It is also at the shorter variable
line lengths that the majority of interactions can be seen. The inclination of the variable line has also been shown to influence judgements of this type of scene.

Some of the effects and interactions appear to stem from the general tendency to overestimate the length of the shorter variable lines. As in the previous experiment, the indications are that the Dark-Medium-Light luminance order has been judged as being longer than the order Light-Medium-Dark, notably where the shorter line lengths are concerned. Since the luminance order Dark-Medium-Light corresponds to the natural world contrast gradient (contrast reducing with distance), these results would again lend support to O'Shea et al.'s (1994) finding that luminance contrast, rather than luminance, is a cue to depth. The only condition where a shorter variable line has been so judged, has been the L-M-D condition with a plain background, a variable line length 7% shorter than the comparison line, and a variable line descending from the observer (see table 4.6), only 48.5% of the judgements being made that the variable line was longer than the comparison line in this condition; adding a ground plane and horizon has increased the 'longer than' judgements to 57.7%.

The manipulation of the inclination of the variable line has been such that only the front or rear object in the line has been resting on the same plane as the objects in the comparison line. In the condition where the variable line descends with distance from the observer, information from object size and from object height in the visual plane would specify similar spatial layouts; this may well account for the single condition
mentioned in the previous paragraph where the variable line was judged to be the shorter.

In this experiment, the luminance order D-M-L has resulted in longer judgements of the variable line length in a majority of cases; that it has not done so exclusively argues that both luminance gradients and luminance contrast gradients can function as cues to depth, and that the relative strength of these two cues is influenced by the other depth information available. This is in accord with the proposal by Landy et al (1991) that before summation, the available cues are weighted both individually, and then by comparison with each other. Given the strength of the correlation with the Shapes Analysis Test, it is possible that, for subjects with a 'weaker' sense of linear perspective, there is a greater potential for the luminance or contrast cues to influence perception of spatial layout.

4.5. Conclusion.

This experiment does provide further support for the view that differences in object luminance will affect judgements of the spatial layout of a scene. Here, there is more support for a luminance contrast gradient as a depth cue than for a luminance gradient, but either has been affected by the other information available.

The three studies using a comparison task will now be considered together.
5. General Discussion.

It seems clear that in the last two studies, the effect of object to background luminance contrast has had a stronger effect on perceptions of the spatial layout of some of the scenes than has luminance per se, the reverse of the previously obtained effects of the luminance variations.

Rohaly and Wilson (1993) hold that (luminance) contrast effects occur at or before the extraction of depth. It may be more accurate to say that contrast effects can occur before (as one form of edge definition) and as part of the extraction of depth. However, for a luminance contrast effect to obtain, information from luminance must also be available. The depth extraction process must, therefore, deal with more than one type of information from any luminance differences between scene components, and in a scene representing part of a 3-dimensioned world, with other information (e.g. from perspective) as well. Part, or all, of the available information must therefore be combined or integrated in some way.

Cue combination.

The first implication of these results, with regard to any process of cue combination, must be that all the available information has been used. In Experiment 3, the luminance gradient and luminance contrast gradient of the variable line are in opposition for the luminance orders L-M-D and D-M-L. If either the luminance gradient or the luminance contrast gradient had been excluded (or consistently zero-weighted), it is unlikely that the interaction between luminance order and line length would have been
obtained. Reference to the graph of this interaction (Figure 4.2), where the lines for the L-M-D and D-M-L luminance orders intersect at a point equivalent to a variable line length 3% shorter than the comparison line, and where each intersects the line for the all-Medium luminance order demonstrates this. Similarly, in Figure 4.4, it can be seen that the addition of a ground plane and horizon line has had an effect on all the luminance orders for the variable line, but then adding texture to the ground plane has only affected the all-Medium luminance order.

While Experiment 3 indicated that the luminance order L-M-D gave rise to more judgements that the variable line was longer than the comparison line, this was not the case for Experiment 4. Removing the centre object from each line, with the intention of reducing the amount of information from linear perspective, has resulted in the luminance gradient and luminance contrast gradient virtually cancelling each other out. This would surely not have occurred had one of the gradients been zero-weighted. In Experiment 5, with another change in the amount and type of information available, it was the luminance order D-M-L that generally gave rise to more judgements that the variable line was longer than the comparison line; however, both luminance orders of the variable line were usually seen as longer than the comparison line, even when it was substantially shorter.

Since Bruno and Cutting (1988) were clear that their simple additive (after weighting) model of cue combination should not be taken as applying to all cues, and the three experiments here suggest that the available cues determine the manner of their combination, another model is required. The two stage model of cue combination
proposed by Landy et al (1991) allows for an evaluation of each cue independently, followed by an evaluation of each cue in the light of the other cues. This model will take into account both the number of cues available, and their strength.

Any discussion of whether cue B supports, or conflicts with, cue A, carries the assumption that cue A is the prime source of information on spatial layout. Should cue C have determined the basic layout, then cue A could become the moderator with cue B being discounted, or given a very low weight, or indeed a high weight. Perspective information may only have primacy as suggested by Pirenne (1972), where it is sufficiently strong to influence the weighting of other available cues, at least for static scenes. All the stimuli used up to this point have been static scenes, whereas simulators in normal use feature some degree of movement. Subsequent experiments, therefore, will employ stimuli in which one of the scene components can be moved by the subjects.
CHAPTER 5: THE BRIGHTNESS EXPERIMENT.

1. Introduction.

The five preceding studies have all supported the view that luminance differences between objects in a scene can influence judgements of the spatial layout of that scene. It is not yet clear whether it is the luminance gradient, or the contrast gradient, across those objects that affects a judgement, since each gradient appears to have been influential on separate occasions. One question that has not yet been addressed is that of whether any of the subjects have been conscious of the degree of the luminance differences, or are capable of accurately assessing the relative luminance of the scene components. Ames (1949) showed both that the brighter of two equally sized areas appeared nearer, and that the larger of two areas of equal luminance appeared brighter.

The relationship between subjective judgements (brightness) and luminance has often been studied using single circular stimuli, presented against a black or near black background, with the subjects being required to estimate the magnitude of the luminance of the stimuli, and the results generally following Stevens' power law (Moyer, Bradley, Sorensen, Whiting and Mansfield, 1973; Stevens, 1975). However, doubts have been cast on the validity of brightness magnitude estimation on the basis that subjects do not handle numbers in a non-linear fashion (Poulton, 1968; Curtis, Attnave and Harrington, 1968; Saunders, 1972; Wagenaar, 1975). The use of a dark background does not relate to the type of scene normally presented on a simulator, nor will the scene show a single
foreground area against the background. This study sought to overcome these problems by requiring subjects to rank, in order of ascending brightness, five apertures in a grey mask covering a screen showing a single colour, and using the phenomena of screen luminance fall off toward the edge to obtain the luminance differences between apertures. The aim of this study was to determine the accuracy with which subjects could judge luminance differences between non-contiguous areas of the monitor screen.


Subjects.

Nine subjects - 3 male, 6 female, took part. All were post-graduates or research staff in the Psychology Department, University of Surrey.

Equipment.

Single colour screens were presented on the BEST display monitor fitted with a mask. On the BEST machine, the intensity of each of the colour guns within the monitor (Red, Green and Blue) can be programmed individually over a range from 0 (minimum) to 255 (maximum). For each nominal colour, the value for that colour was set at 220, with the other two values set at 120. Thus the "Green" screen had the colour values set at Green 220, Red 120 Blue 120. This principle was followed for the "Red" and Blue" screens. The luminance values obtained are shown below in Table 5.1.
Table 5.1: Luminance values and aperture sizes.

<table>
<thead>
<tr>
<th>APERTURE LUMINANCE VALUES (cd/m²)</th>
<th>APERTURE NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCREEN COLOUR</td>
<td>1</td>
</tr>
<tr>
<td>RED</td>
<td>40.7</td>
</tr>
<tr>
<td>GREEN</td>
<td>33.4</td>
</tr>
<tr>
<td>BLUE</td>
<td>130.0</td>
</tr>
</tbody>
</table>

The mask, of 1.5 mm card, was shaded a pale grey (luminance 20 cd/m²), and had square apertures at the centre and at the four corners, with one top and one bottom corner being larger (40mm square) than the others (35mm square). The small corner apertures (numbers 2 and 4) were set in toward the screen centre by 12mm on the screen diagonal, in order that the luminance reading at the centre of each of these apertures was slightly higher than for the larger ones. Although the overall luminance varied between colours, the percentage fall-off from screen centre to each of the corners was consistent to within 1.5%, within an overall range of between 15% and 31%. The aperture layout was:

```
2   1
5
4   3
```
Procedure.

Subjects were seated at a 1.4 metres viewing distance from the masked screen. They were given a response sheet containing four groups of five boxes, each group corresponding to the apertures in the mask, and asked to rank these apertures in increasing order of brightness. A grey screen was presented while they were given their instructions, and they used this for a practice, after which the three coloured screens were presented. No time limit was imposed.

3. Results.

The mean rank across subjects for each aperture and each colour is shown below:

<table>
<thead>
<tr>
<th>APERTURE NO.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIZE (mm sq.)</td>
<td>40</td>
<td>35</td>
<td>40</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>TRUE RANK</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

OBSERVED RANKS

- RED
  - 2.72
  - 1.61
  - 4.77
  - 2.50
  - 3.17

- BLUE
  - 1.83
  - 1.66
  - 3.94
  - 4.00
  - 3.22

- GREEN
  - 3.05
  - 1.77
  - 3.88
  - 2.84
  - 3.33

Analysis of Variance by Ranks shows the effect attributable to Apertures as significant (n=9; F=11.06; d.f.=4; p > 0.001) whilst that attributable to Colour was not (F=1.0; d.f.=2; p=0.39). These effects were consistent across subjects, as shown by Kendall's Co-efficient of Concordance:

<table>
<thead>
<tr>
<th>COLOUR</th>
<th>W</th>
<th>Chi-Square</th>
<th>d.f.</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>RED</td>
<td>.5331</td>
<td>19.19</td>
<td>4</td>
<td>.0007</td>
</tr>
<tr>
<td>BLUE</td>
<td>.5237</td>
<td>18.85</td>
<td>4</td>
<td>.0008</td>
</tr>
<tr>
<td>GREEN</td>
<td>.2636</td>
<td>9.49</td>
<td>4</td>
<td>.05</td>
</tr>
</tbody>
</table>
A mean rank across subjects and colours was calculated for each aperture, and these figures were correlated with the mean luminance across colours (cd/m²) and the mean luminous energy (cd/m² x area) for each aperture. The results (for d.f. = 3) show:

<table>
<thead>
<tr>
<th></th>
<th>r</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminance</td>
<td>.3681</td>
<td>.542</td>
</tr>
<tr>
<td>Energy</td>
<td>.8946</td>
<td>.04</td>
</tr>
</tbody>
</table>

Thus the subjects’ rankings of the luminance of the apertures appears to be related to the size of the aperture, with a tendency to judge the larger apertures as being brighter than they actually were, even when the actual light energy emitted (luminance x area) was over 35% less. This supports the 'Brighter = Larger' finding of Ames (1949).

4. Discussion.

From the above study, it can be seen that subjects consistently misjudged the relative luminance of non-contiguous areas. The association between size and luminance may not be valid, but its existence - at least for the subjects here - showed clearly that a larger area was perceived as being brighter than a smaller area, even when the smaller area was of greater luminance. The effect on judgements of relative distance was not explored here, there was no spatial layout to be judged, and thus no potential conflict between cues. However, since all five preceding studies suggest that either the luminance gradient or the contrast gradient across objects, has influenced judgements of their spatial layout, the apparent relationship between object size and perceived brightness cannot be
ignored, even if the observers cannot make accurate assessments of the relative brightness of non-contiguous areas or objects.

5. Conclusion.

The results obtained here argue that real object size information can overrule luminance information. The next experiment will require subjects to match the size of a stimulus, when luminance and contrast are manipulated.
1. Introduction.

All the previous experiments have used stimuli without any movement of individual components; simulators for any type of vehicle have either a moving scene or moving components within the scene, with some degree of observer control over that movement. Having shown that luminance differences between scene components in static stimuli can influence perceptions of their relative position - either directly, or indirectly from contrast differences - this last series of experiments looked at the effect of varying the luminance of an object which could be moved in the scene by the observer.

The previous experiments have also shown the need for adequate information from linear perspective if observer judgements are to be reasonably accurate. In any scene with movement, the movement itself can offer additional information. Motion in any direction can potentially lead to interposition between scene components, and this has been shown to be a more powerful depth cue than information from luminance (Rhodes, 1980; Reinhart, Beaton and Snyder, 1990). The stimuli used in this series will avoid any interposition or occlusion of static scene components by the moving object, to obviate any influence from this cue.
Axial motion of the moving object will cause the size and position of its image on screen, and hence that of its retinal image to alter; the moving object image will change size relative to the static scene components, its height relative to the horizon - if present - and to the rest of the scene, will alter, and the exponential rate of change in size (within those limitations of scaling in pixel units discussed in chapter 2) will provide further information. The relative size of the moving object will continue to provide a pictorial cue (DeLucia, 1991) at any time that the object is not in motion. Each of these cues can potentially strengthen the impression of depth, and these cues will not normally be in conflict.

The experiments in this series.

All the preceding experiments have indicated that the inter-object luminance differences have had some influence on the judgements made by the subjects. Whilst this requires that the subjects be aware of the differences, this could be at the unconscious level, or the subjects could be using their assessment of the different luminance levels to form their judgements. The luminance experiment reported in the previous chapter did, however, indicate that subjects’ judgement of luminance was influenced by the size of the luminous area.

This series starts with a size matching task: size adjustment being accomplished by moving a rectangular plane surface along the axis of vision, with luminance and contrast being manipulated. The penultimate experiment retains the plane surface moving object,
with subjects being required to locate it at specified locations within a 3-D scene, and the final experiment uses a similar task but with a 3-D moving object. There is, therefore, a progressive increase in the amount of depth information available.

2. EXPERIMENT 7

2.1. Introduction.

The first five studies have shown that luminance differences between objects in a scene containing other depth information, presented on a CRT screen, will affect judgements of the spatial layout of that scene. Three of the studies suggest that object luminance - in the form of the luminance gradient between objects - has been the moderating factor, while the remainder support the view that contrast has a greater influence than luminance. One common factor in all these studies has been the availability of depth information from linear perspective.

The results of Experiment 6 suggest that observers associate greater area with greater luminance as Ames (1949) has demonstrated. The Ames demonstration using two internally illuminated balloons can be summarised as:

- Brighter = Nearer (balloons of equal size)
- Larger = Brighter (balloons of equal luminance)

and, in logical terms, it should follow that Larger and Nearer are also equal. Given two identical objects, that which is nearer will subtend a larger image on the retina, and the link between size and distance is, in this case, valid.
However, neither Ames (1949), or Experiment 6 here, had any systematic control of contrast.

O'Shea, Blackburn and Ono (1994) had a systematic variation of contrast by altering background luminance, but required only a decision between two foreground areas of equal size, differing only in luminance, as to which one appeared nearer. Their conclusions were that the area of greatest contrast with the background appeared nearer, they did not, however, ask for any judgements on the degree of nearness. Ross (1968, 1993) required judgements of absolute distance on a range of identical sized targets, of varying shades of grey, viewed at a constant distance through turbid water. Her finding was that for targets lighter than the background, the distance estimates increased with a reduction in target luminance, with the reverse true when the targets were darker than the background.

None of these studies offered information from linear perspective, and the two that used a monitor to display the stimuli (Experiment 6, and O'Shea, 1994) were not interactive in the sense of the observer having any control over the display. The importance of linear perspective has been shown in Experiments 1 to 5, but the relationship between object size, luminance, and contrast, when the observer has control over depicted object size, has not yet been explored.
The present study sought to avoid the problem of brightness magnitude estimation by using a size matching task. This required observers to vary the size of one object (a horizontal bar) to match that of a similar bar in a stimulus in which luminance, contrast, or both, were varied across a range of values, without any other depth information being present. The depicted size of the response bar was adjusted by altering its distance from the stationpoint. Thus, Foreground Luminance, Background Luminance, the Contrast between them, and the depicted size of the two bars was the only information available to the subjects, while the location of the adjustable bar on the z-axis would provide a measure of the depicted size to which it had been adjusted.

From the arguments regarding luminance or contrast as the more influential cue to distance, it can be predicted that if the foreground bar has a higher luminance than the background:

A) Increasing both the foreground and background luminance in such a manner as to hold contrast constant should not lead to differences in the adjusted position of the foreground object if contrast is the more powerful cue, but to its being placed further away if luminance is the more influential.

B) Increasing the luminance of the foreground object while holding background luminance constant, would lead to its being perceived as larger (or nearer), and thus in a size matching task to its being positioned further away, whether luminance or contrast be more influential.
C) Holding foreground luminance constant whilst increasing that of the background, should lead to the foreground object being placed with an increase in background luminance if contrast is more influential, but should not lead to any variation if luminance is the more powerful cue.

2.2. Method

Subjects.

Eight subjects took part: 5 female and 3 male. All were first year psychology students.

Equipment

The scenes.

The stimulus was a horizontal grey bar, 100 units wide, 10 units high (giving 100mm x 10mm on the monitor screen), with a blue background. This was located centrally on the horizontal axis of the display monitor. Either the luminance of the bar, or the background, or both, were increased over a 7-step range, giving three series of stimuli. Regardless of which component was being varied, step 4 in each series was identical. The luminance values were generally lower than those used in Experiments 1 to 5; this enabled the Michelson contrast values to be matched in the two conditions where only one scene component varied in luminance.
### Luminance Values (cd/m²) and Michelson Contrasts

<table>
<thead>
<tr>
<th>STEP</th>
<th>CONDITION 1</th>
<th>CONDITION 2</th>
<th>CONDITION 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BAR</td>
<td>CONTRAST</td>
<td>GROUND</td>
</tr>
<tr>
<td>1</td>
<td>39.1</td>
<td>.239</td>
<td>24.0</td>
</tr>
<tr>
<td>2</td>
<td>44.0</td>
<td>.294</td>
<td>24.0</td>
</tr>
<tr>
<td>3</td>
<td>49.1</td>
<td>.343</td>
<td>24.0</td>
</tr>
<tr>
<td>4</td>
<td>54.9</td>
<td>.389</td>
<td>24.1</td>
</tr>
<tr>
<td>5</td>
<td>60.5</td>
<td>.430</td>
<td>24.1</td>
</tr>
<tr>
<td>6</td>
<td>66.6</td>
<td>.468</td>
<td>24.1</td>
</tr>
<tr>
<td>7</td>
<td>73.1</td>
<td>.502</td>
<td>24.2</td>
</tr>
</tbody>
</table>

Table 6.1: Luminance values.
The limitations imposed by the available range of colour gun settings on the BEST did require a small measure of compromise with regard to the luminance values (mainly in Condition 3), but this was of less importance than having an imbalance in the contrast values between conditions 1 and 3. The luminance and contrast values are given in Table 6.1. A fourth series which started with a green bar, had steps 2 to 6 identical with step 4 in conditions 1, 2 and 3, and finished with a red bar, was used as a marker, and made a baseline score available from repeated trials on a constant stimulus. In terms of the progression through each series, the three conditions were:

- **Condition 1**
  - Bar increases in luminance
  - Background is constant
  - Contrast increases

- **Condition 2**
  - Bar increases in luminance
  - Background increases in luminance
  - Contrast is constant

- **Condition 3**
  - Bar is constant
  - Background increases in luminance
  - Contrast decreases
  (Note: the apparent effect is of a decrease in the luminance of the bar.)

The step to step changes in each condition are of equal interval as regards to contrast, and approximate to equal interval in the case of luminance.

**Presentation equipment.**

Two BEST simulators were used for this study, with the display monitors located side by side, and at the same height. A small screen was placed between the two monitors to eliminate stray reflections from the equipment, while permitting subjects a binocular...
view of each screen. The stimuli were presented on the right hand monitor, controlled by the experimenter, while the left hand monitor was used to obtain the subject response. This monitor displayed the Step 4 scene common to all three conditions, set to identical luminance and contrast values, with subjects able to adjust the size of the foreground bar with the joystick control on the BEST console. The size variation was actually accomplished by moving the bar nearer to, or further away from, the virtual stationpoint. This made positional data available via the BEST data-logging system.

Procedure.

Subjects were seated on the centreline between the two monitors, 1.4 metres from the plane of the screens, with the control console for the left monitor positioned so that the joystick controlling the bar on that display was also on the centreline. A written set of instructions required them to adjust the size of the bar with the joystick so as to match the width of the bar presented on the right monitor. The experimenter sat to the subjects' right, controlling the change of stimuli on a second console. The layout of the equipment is shown in Figure 6.1.

Each series was pseudo-randomised using the same sequence: 1-6-2-4-5-3-7. The series were presented in pseudo-random order, with no subject getting the same sequence twice. Each session presented two runs through series 1 to 3, and one run through the distracter series. The starting point for each session was the "green bar" from the
Figure 6.1: Equipment layout for Experiment 7.
distracter series, the appropriate experimental series was then selected and the seven views presented, and the distracter series selected again to show a "red bar" screen. On presentation of each view, the subject adjusted the bar on the left hand monitor to match for width, and pressed the BEST log key. The experimenter then moved the joystick to change the bar size, and selected the next view.

Five sessions were run for each subject. This gave 10 trials for each of 7 steps, in each of 3 conditions, and 25 trials of the baseline view. In adjusting the bar width, subjects were in fact moving it closer to, or further from the virtual eye position of the simulator, and the data obtained were measures of the distance of the bar. These data were converted into error scores with "Too Large", i.e. too close, being shown as a minus value, and "Too Small" (too far away) as a positive value.

Design.

A repeated measures design was used. In each condition, the difference between the Subject mean scores from the baseline series and the Step 4 scores was subtracted from each score in steps 1, 2, 3, 5, 6 and 7. This gave an error score corrected to the baseline.
2.3 Results

For each subject, a mean corrected error score across the ten trials for each of the seven steps in each of the three conditions was calculated. The mean error score across subjects for each step, in each of the three conditions, is shown in Table 6.2.

Table 6.2: Error scores.

<table>
<thead>
<tr>
<th>STEP</th>
<th>CONDITION 1</th>
<th>CONDITION 2</th>
<th>CONDITION 3</th>
<th>MEANS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN</td>
<td>S.D.</td>
<td>MEAN</td>
<td>S.D.</td>
</tr>
<tr>
<td>1</td>
<td>2.46</td>
<td>5.64</td>
<td>3.55</td>
<td>3.47</td>
</tr>
<tr>
<td>2</td>
<td>0.52</td>
<td>3.86</td>
<td>0.89</td>
<td>5.81</td>
</tr>
<tr>
<td>3</td>
<td>2.06</td>
<td>3.93</td>
<td>1.78</td>
<td>2.23</td>
</tr>
<tr>
<td>4</td>
<td>2.20</td>
<td>4.07</td>
<td>2.68</td>
<td>3.13</td>
</tr>
<tr>
<td>5</td>
<td>-0.34</td>
<td>4.49</td>
<td>1.13</td>
<td>5.55</td>
</tr>
<tr>
<td>6</td>
<td>1.70</td>
<td>4.58</td>
<td>1.05</td>
<td>2.35</td>
</tr>
<tr>
<td>7</td>
<td>2.94</td>
<td>5.14</td>
<td>-0.05</td>
<td>4.71</td>
</tr>
<tr>
<td>MEANS</td>
<td>1.65</td>
<td>1.57</td>
<td>0.92</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Analysis of variance on the factors of Conditions and Steps showed no significant main effects or interaction. No condition shows a linear progression through the seven steps. Table 6.2 also shows that the Standard Deviations are substantial when compared to the means. Table 6.3, below, shows the means across subjects of the within-subjects Standard Deviations.
Table 6.3: Means across subjects of the standard deviations.

<table>
<thead>
<tr>
<th>Step</th>
<th>Condition 1 Bar increases in luminance</th>
<th>Condition 2 Bar and background increase</th>
<th>Condition 3 Background increases in luminance</th>
<th>Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.07</td>
<td>8.98</td>
<td>9.05</td>
<td>9.34</td>
</tr>
<tr>
<td>2</td>
<td>8.10</td>
<td>8.98</td>
<td>9.39</td>
<td>8.82</td>
</tr>
<tr>
<td>3</td>
<td>9.41</td>
<td>11.09</td>
<td>7.58</td>
<td>9.36</td>
</tr>
<tr>
<td>4</td>
<td>9.76</td>
<td>8.84</td>
<td>8.97</td>
<td>9.19</td>
</tr>
<tr>
<td>5</td>
<td>10.39</td>
<td>8.74</td>
<td>8.73</td>
<td>9.29</td>
</tr>
<tr>
<td>6</td>
<td>8.79</td>
<td>7.64</td>
<td>9.12</td>
<td>8.58</td>
</tr>
<tr>
<td>7</td>
<td>8.42</td>
<td>8.40</td>
<td>10.54</td>
<td>9.12</td>
</tr>
<tr>
<td>Means</td>
<td>9.28</td>
<td>8.95</td>
<td>9.05</td>
<td>9.09</td>
</tr>
</tbody>
</table>

The smallest mean standard deviation across steps is that for Condition 2, where the contrast was held constant, but this same condition also has the greatest range of standard deviations. Analysis of variance on the factors of Condition and Step, using the subject Standard Deviations as the dependent variables showed:

Main Effects:
- Condition: df = 1,7, f = 0.85, p = .450
- Step: df = 6,42, f = 0.82, p = .557

Interaction:
- Condition x Step: df = 12,84, f = 1.93, p = .042

The data for standard deviations are shown graphically in Figure 6.2, where it can be seen that there is no consistent stepwise pattern. The two conditions where the background luminance varies (2 and 3) are almost mirror images of each other; they are very close for step 4 (the step with identical stimuli in each condition), whilst Condition 1 is not.
Figure 6.2: Standard deviations: means across subjects:
Examination of the individual subject scores, when related to the change in the stimulus from the previous trial, revealed that an average of 48.6% of judgements had followed the direction of change in luminance from the previous trial; an increase in luminance - whether of bar or background - led to the bar being positioned further away. Table 6.4 below shows the number of subjects who have followed the change in luminance, by condition.

Table 6.4: Judgements following change in luminance.

<table>
<thead>
<tr>
<th>Frequency table: number of subjects following direction of change in luminance (bar, background, or both).</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Table" /></td>
</tr>
</tbody>
</table>

For each subject, a percentage score for each condition was calculated. The difference in the mean scores between Condition 2 (mean 45.44%) and Condition 3 (mean 51.86%) is significant (df = 7, t = -2.44, p = .045, 2-tailed). The percentage data are shown graphically by subject in Figure 6.3.

Conditions 2 and 3 are those where the background luminance increases by approximately equal intervals with each step (see Table 6.1 above), with contrast held constant for Condition 2 and varied in Condition 3. This argues that changes in background luminance can also have a significant effect, but this is not consistent across subjects. Reference to Table 6.4 and Figure 6.3 (following) will show that while every
subject has followed the direction of stimulus change in at least one condition to a degree
greater than chance, only two have done so in more than one condition. This implies
that there are individual differences with regard to the effect of stimulus change, and,
if the size of the Standard Deviations is also considered, would suggest that no single
adjustment (or judgement) would be particularly reliable, a conclusion also arrived at by
Ross (1993).

2.4 Discussion.

The results have not enabled a comparison between the relative power of luminance and
contrast as sources of depth information. In this study, subjects were required to adjust
a bar for size by varying its distance, and it could be argued that both luminance and
contrast changes have influenced subjects' perceptions of the size of the moving object,
which in turn may influence their judgement of relative distance. Here, the only
information available was the luminance of the foreground bar and background, and the
contrast between them. That the results obtained were much lower significance levels
than in the previous studies does argue that both luminance and contrast are, in
themselves, weak cues to depth. Luminance or contrast gradients, supporting or
conflicting with other depth information have been shown in the earlier studies to be
more powerful.

It was not expected that the overall luminance (which in this case is predominantly the
background luminance) would lead to the effect shown in Table 6.4. O'Shea et al
(1994) compared the effects of variation in background luminance with changes in the foreground to background size ratio, and determined that whilst both main effects (but not the interaction) were significant, the foreground to background size ratio had a stronger effect. However, if the total luminous energy emitted by the screen is considered, their study is not directly comparable with this present one. Here, the background always made by far the largest contribution to the total luminous energy emitted, whilst in the O'Shea et al (1994) study, not only could the foreground be the major contributor in some conditions, but the total energy emitted by the monitor screen exceeded the maxima in this study by factors between x 1.2 and x 5 depending on condition. A final point concerns the manner in which some subjects were apparently influenced by the previous stimulus. Vrolijk (1986) showed that response to one stimulus can be affected by an earlier stimulus, and it may well be that the results obtained here were confounded by this effect.

2.5. Conclusion.

The results obtained here suggest that any single judgement in a task of this nature may well be inaccurate, and that the overall luminous energy emitted by the display may have as great an influence as the luminance differences between components in the scene portrayed when there is no information from linear perspective. In this experiment, there was no information from linear perspective: the next study will therefore use a plane surface as the adjustable object, but this will move within a scene offering perspective information.
3. EXPERIMENT 8.

3.1. Introduction.

Looking at the first five experiments, it can be said that if there has been sufficient information from linear perspective to specify the general layout of a scene, then it has been luminance gradients rather than contrast that have moderated the perspective information, with a general effect of Brighter being equated with Nearer. This would support Pirenne's (1970) view of the primacy of linear perspective in establishing the spatial layout of the scene. When the perspective information has been inadequate, then the results have followed O'Shea, Blackburn and Ono (1993) in that Greater Contrast has been equated with being Nearer, possibly to the point where contrast information has been the prime specifier of scene layout. The two experiments which have not portrayed scenes in depth, have indicated that observers do not generally make good judgements of the relative luminance, or the size, of non-contiguous areas.

For this experiment, the size matching task in Experiment 7 was replaced with a positioning task, retaining a plane surface for the object controlled by the observer, while the static components in each scene offered perspective information, and specified a scene in depth. In any scene with movement, the movement itself can offer additional information. Motion in any direction can potentially lead to interposition between scene components, and this has been shown to be a more powerful depth cue than information from luminance (Rhodes, 1980; Reinhart Beaton and Snyder, 1990). The scenes in this
experiment have been designed so that no interposition is possible, and thus no information from interposition is available to confound the results. Limited information from the trajectory of the moving object will, however, be available.

Axial motion of the moving object will cause the size and position of its image on screen, and hence that of its retinal image to alter; the moving object image will change size relative to the static scene components, its height relative to the horizon - if present - and to the rest of the scene will alter, and the exponential rate of change in size (within the pixel scaling limitations already discussed) will provide further information. The relative size of the moving object will continue to provide a pictorial cue (DeLucia, 1991) at any time that the object is not in motion.

The aim of this experiment is to determine whether luminance or contrast information will affect judgements in a positioning task when the moving object offers no perspective information, while perspective information from the static scene components specifies a scene in depth. As in previous experiments, it was assumed that if an object has to be positioned at an exact location and its luminance is varied, and an increase in luminance leads to the percept that it is nearer, that the increase in luminance will cause it to be positioned further away from the observer.
3.2. Method.

Subjects.

Eighteen subjects - 13 female and 5 male - took part. All were students in the Psychology Department, University of Surrey.

The stimuli.

For this experiment, a simple landscape was used. A blue "sky" background and green ground plane provided a horizon line, and two static objects were positioned on the ground plane. These took the form of parallel walls, 30 units high, 10 units wide and 200 units long. They were 100 units apart. The moving object (MO) was a vertical plane surface, 30 units high, 10 units wide, with its base 1 unit above the ground plane. The MO was located on the centreline of the alley formed by the walls and could traverse this line. The axis of view was 33 units above the ground plane, and either along the centreline of the alley, or parallel to it but laterally displaced 5 units to right or left. Thus, the MO could move along (but just below) the axis of vision, or at an angle to it, giving some measure of trajectory information. The general scene layout is shown in Figure 6.4.
Figure 6.4: Typical stimulus scene.
Three types of scene were used in this experiment. The background (green ground plane, blue sky) were always equiluminant, and the MO (grey) was lighter than, darker than, or equiluminant with the background.

Luminance values for the scenes were:

<table>
<thead>
<tr>
<th></th>
<th>Moving Object</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark on Light</td>
<td>15 cd/m²</td>
<td>65 cd/m²</td>
</tr>
<tr>
<td>Light on Dark</td>
<td>60 cd/m²</td>
<td>21 cd/m²</td>
</tr>
<tr>
<td>No Contrast</td>
<td>40 cd/m²</td>
<td>40 cd/m²</td>
</tr>
</tbody>
</table>

The alley walls were shaded (in grey) so that the front face was closer in luminance to the background than to the MO, one inside face was made brighter, and one darker than the MO, but each face always offered a contrast to the background and to the MO.

**Presentation equipment.**

The stimuli were presented on the BEST display monitor. The control console was positioned so that the joystick controlling forward and backward motion of the MO was in line with the centre of the screen. This, and the key activating the BEST data logging function, were the only controls available to the subjects, who were seated 1.4 metres from the screen and centrally in front of it. Thus, subjects could use either hand to operate the joystick. The experimenter was positioned to the left of, and slightly behind the subject; a position offering easy access to the view and palette controls on the console. The layout is shown in Figure 6.5.
Figure 6.5: Equipment layout for Experiment 8.
Procedure.
Subjects were seated at the control console and given a set of written instructions, an illustration of the nature of the scene, and a diagram illustrating the task. They were required to position the MO so that it was alternately aligned with the front faces of the walls of the alley, or the rear faces. After each positioning, subjects pressed the data logging key to record the position of the MO.

There were 20 trials for each location where the axis of view was straight along the centre of the alley, and 10 trials for each of the two views at an angle. After each series of trials, the experimenter changed the colour palette and direction of view, and pressed the logging key three times to mark the end of each series. No time limit was imposed. Thus, 10 subjects each made 20 trials for each of 3 scenes x 2 angles of view x 2 target locations.

3.3. Results.
The raw MO positions were converted into error scores: positions too close to the observer being given a negative value, and those too far away a positive value. The scores for each subject for the two opposing angles of view were combined. The mean scores across subjects are shown below in Table 6.5.
Table 6.5: Positional error scores.

<table>
<thead>
<tr>
<th>VIEW</th>
<th>SCENE</th>
<th>MEAN</th>
<th>FRONT</th>
<th>REAR</th>
<th>MEAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRAIGHT</td>
<td>DARK on LIGHT</td>
<td>MEAN</td>
<td>-12.82</td>
<td>-24.76</td>
<td>-18.79</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td></td>
<td>15.25</td>
<td>56.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LIGHT on DARK</td>
<td>MEAN</td>
<td>-14.96</td>
<td>-27.24</td>
<td>-21.10</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td></td>
<td>16.55</td>
<td>49.48</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NO CONTRAST</td>
<td>MEAN</td>
<td>-14.26</td>
<td>-40.72</td>
<td>-27.49</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td></td>
<td>11.92</td>
<td>33.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MEANS</td>
<td></td>
<td>-14.01</td>
<td>-30.9</td>
<td>-22.46</td>
</tr>
<tr>
<td>ANGLE</td>
<td>DARK on LIGHT</td>
<td>MEAN</td>
<td>-12.71</td>
<td>-25.44</td>
<td>-19.07</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td></td>
<td>14.09</td>
<td>41.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LIGHT on DARK</td>
<td>MEAN</td>
<td>-11.06</td>
<td>-24.99</td>
<td>-18.02</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td></td>
<td>14.2</td>
<td>38.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NO CONTRAST</td>
<td>MEAN</td>
<td>-10.24</td>
<td>-29.74</td>
<td>-20.08</td>
</tr>
<tr>
<td></td>
<td>S.D.</td>
<td></td>
<td>11.01</td>
<td>40.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MEANS</td>
<td></td>
<td>-11.34</td>
<td>-26.72</td>
<td>-19.03</td>
</tr>
</tbody>
</table>

It can be seen that there is a consistent tendency to place the MO too close to the observer, that the error is larger for the rear location, and that there is a slight improvement with the angled view. For either view, the moving object is placed much closer to the observer in the far position if there is no luminance contrast between MO and background.
Analysis of variance on the means across subjects for the factors of Scene Luminance, Target Location and View shows the following:

**Main effects:**
- **Scene**
  - df=2,34
  - $f=3.29$
  - $p = .049$
- **Location**
  - df=1,17
  - $f=0.57$
  - $p = .460$
- **View**
  - df=1,17
  - $f=8.29$
  - $p = .010$

**Interactions:**
- **Scene x Location**
  - df=2,34
  - $f=3.34$
  - $p = .047$
- **Scene x View**
  - df=2,34
  - $f=3.10$
  - $p = .058$
- **Location x Angle**
  - df=1,17
  - $f=3.11$
  - $p = .096$

**Three way interaction:**
- **Scene x Location x View**
  - df=2,34
  - $f=3.44$
  - $p = .043$

Thus of the main effects, the Angle of View and the Scene Luminance are both significant. Only the interactions of Scene x Location, and of Scene x Location x View are significant, although the others are close to being so. It can be said that no one factor has a major influence on the mean error scores.

The interaction between Scene and Location is shown in Figure 6.6, below. It can be seen that whilst the mean error score for the No Contrast condition is the smallest for the Near Target Location, it is the largest for the Far Location. This figure also shows that the MO with a luminance greater than the background - contrast ratio .506 - is placed nearer to the observer than the MO with a luminance darker than the background - contrast ratio .625. This is in accord with the findings of O’Shea *et al* (1994).
Figure 6.6: Interaction: Scene and target location.
When considering the three-way interaction, the scores for the Straight view generally follow the pattern above, but there is a reversal between the two conditions with MO to background contrast for the Angled view. Apart from the No Contrast scene at the Far location, the differences are small.

3.4. Discussion.

This experiment has shown somewhat similar results to those of Experiment 7, in that the general quality of positional judgement was poor. One item of information that was available was that of size, specifically the height of the moving object compared to the height of the alley walls. Subjects were informed in the instructions that these were identical, yet to judge from the standard deviations, they were either not making use of this information, or, as in Experiment 7, were generally unable to judge it with any degree of accuracy. Even without interposition, the limited extra information from the trajectory in the angled view condition was significant.

There was no effective difference between the two directions of luminance gradient, and the significant main effect of Scene Luminance is probably due solely to the greater underestimation of position at the far target location in condition 3 (no contrast). This suggests that object-to-background contrast has been a more influential source of information than object luminance or the direction of the luminance gradient.
3.5. Conclusion.

These last two experiments have shown similar results as regard to the poor quality of positional judgements when a movable object offers no information from linear perspective. The final experiment will employ scenes offering more information from linear perspective, and in which the moving object is clearly portrayed as being three-dimensional.
4. EXPERIMENT 9.

4.1. Introduction.

In the previous experiment, the moving object was a 2-D plane surface, normal to the z-axis of the scene, that had to be positioned level with the front and back edges of two walls forming an alley, and disposed around the z-axis. Thus, the static components specified a 3-D scene with a single vanishing point, while the moving object itself offered no perspective information. In normal applications, simulators for any type of vehicle have either a moving scene or moving components within the scene, with some degree of observer control over that movement, and all scene components specified in three dimensions. Thus, not only will the relative size of the moving object offer a pictorial cue (DeLucia, 1991) at any time that the object is not in motion, perspective information from the moving object will offer a further pictorial cue. If this information is sufficient to specify the spatial layout of the scene at any given moment, it could be expected, on the basis of the first five experiments here, that luminance information (following Ames, 1949) rather than contrast information (following O'Shea, Blackburn and Ono, 1993; Ross, 1993) would moderate perception of the scene layout.

The aim of this study is to determine if the effects of luminance variations on perceptions of relative distance will still obtain when the observer has some control over the movement of the object being so varied, when both the static scene components and the moving object offer information from linear perspective. It was assumed that if an
object has to be positioned at an exact location, the luminance of that object is varied, and an increase in luminance leads to the percept that it is nearer, then that same increase in luminance will cause it to be positioned further away from the observer.

4.2 Method.

Subjects.

Ten subjects - 7 female, 3 male - took part. All were students in the Psychology Department, University of Surrey.

The stimuli.

For this study a more detailed landscape was created on the BEST (see Figure 6.7). A blue "sky" background, and a green ground plane provided a horizon line, and four static objects were positioned on the ground plane. The static objects were pyramids, 35 units high, 30 x 30 unit base, with their apices positioned over the corners of an imaginary rectangle, 100 units wide and 200 units long. The moving object took the form of a truncated pyramid on wheels; it was 15 units wide at the base, 10 at the top, and 15 units high, with 3 unit high wheels. The stationpoint was located 10 units above the ground plane with the axis of vision rotated 10° to the right and to the left. The moving object (MO) was located on the long axis of the rectangle formed by the pyramids and could traverse this axis. In so doing, its movement was at an angle to the axis of vision, giving some measure of trajectory information.
Figure 6.7: Typical stimulus landscape.
There were two basic scenes: the "Light" and the "Dark" sets. The ground plane and background were not altered between the two sets, but the shading of the pyramids was Light or Dark grey, with the side faces slightly lighter than the front face to strengthen the illusion of depth. The MO had one of four shades for each scene, Dark, Medium Dark, Medium Light, and Light grey. The first two were darker than the pyramids and the second two were lighter.

Luminance values for the scenes were:

<table>
<thead>
<tr>
<th></th>
<th>Sky</th>
<th>Ground plane</th>
<th>Dark Set:</th>
<th>Light Set:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Pyramids</td>
<td>86 cd/m²</td>
<td>185 cd/m²</td>
<td>73 cd/m²</td>
<td>104 cd/m²</td>
</tr>
<tr>
<td>Moving object</td>
<td></td>
<td></td>
<td>63 cd/m²</td>
<td>93 cd/m²</td>
</tr>
<tr>
<td>Dark</td>
<td></td>
<td></td>
<td>44 cd/m²</td>
<td>66 cd/m²</td>
</tr>
<tr>
<td>Medium Dark</td>
<td></td>
<td></td>
<td>93 cd/m²</td>
<td>122 cd/m²</td>
</tr>
<tr>
<td>Medium Light</td>
<td></td>
<td></td>
<td>123 cd/m²</td>
<td>160 cd/m²</td>
</tr>
<tr>
<td>Light</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In normal operation, the joystick used for forward and backward object movement on the BEST is arranged so that moving it away from the observer also moves the object away. To remove any bias due to this, the scenes were duplicated using a reversed joystick operation.
Presentation equipment.

The stimuli were presented on the BEST display monitor using an identical setup to the previous experiment.

Procedure.

Subjects were seated at the control console and given a set of written instructions, an illustration of the nature of the scene, and a diagram illustrating the task. They were required to position the MO so that it was alternately exactly central on lines drawn through the base centres of the front pair of pyramids, and the rear pair (see Figure 6.7). The starting point was equidistant from the two pairs. After each positioning, subjects pressed the data logging key to record the position of the MO. After each series of trials, the experimenter changed the colour palette and direction of view, and pressed the logging key three times to mark the end of each series. No time limit was imposed.

Thus, 10 subjects each did 5 trials for each of two background scenes x two directions of joystick movement x two angles of view x 4 values of MO luminance x 2 target locations.
4.3. Results.

The raw MO positions were converted into error scores: positions closer to the observer than the correct position being given a negative value, and those too far away a positive value. The mean scores across subjects, across the two directions of view and two directions of joystick movement are shown below in Table 6.6. These scores are in the arbitrary "units" used in the BEST programming language.

Table 6.6: Positional error scores.

<table>
<thead>
<tr>
<th>POSITION</th>
<th>SCENE</th>
<th>MOVING OBJECT LUMINANCE (1 DARKEST - 4 LIGHTEST)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>FRONT</td>
<td>DARK</td>
<td>MEAN</td>
<td>-6.07</td>
<td>-6.03</td>
<td>-3.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S.D</td>
<td>10.1</td>
<td>12.32</td>
<td>13.38</td>
</tr>
<tr>
<td></td>
<td>LIGHT</td>
<td>MEAN</td>
<td>-2.26</td>
<td>-3.66</td>
<td>-3.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S.D</td>
<td>12.23</td>
<td>13.43</td>
<td>12.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MEAN</td>
<td>-4.16</td>
<td>-4.85</td>
<td>-3.46</td>
</tr>
<tr>
<td>REAR</td>
<td>DARK</td>
<td>MEAN</td>
<td>-9.56</td>
<td>-5.88</td>
<td>-2.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S.D</td>
<td>20.64</td>
<td>21.89</td>
<td>22.26</td>
</tr>
<tr>
<td></td>
<td>LIGHT</td>
<td>MEAN</td>
<td>-10.8</td>
<td>-10.04</td>
<td>-5.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S.D</td>
<td>22.18</td>
<td>23.06</td>
<td>32.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MEAN</td>
<td>-10.22</td>
<td>-7.96</td>
<td>-3.87</td>
</tr>
</tbody>
</table>
It can be seen that for the rear location, as the MO luminance is increased, it is consistently placed further away, indicating that it is seen as nearer (or larger). The pattern is not quite so clear for the front location, in that the lowest luminance is placed further away than the next higher value.

Analysis of variance on the subject means (collapsed across direction of joystick operation, and angle of view) for the factors of scene type, object luminance, and location of target position, shows the following:

Main effects:
- Scene: df=1,9  f=0.31  p=.591
- Location: df=1,9  f=0.05  p=.829
- Luminance: df=3,27 f=8.09  p=.001

Interactions:
- Scene x Location: df=1,9  f=3.02  p=.116
- Scene x Luminance: df=3,27 f=1.34  p=.282
- Location x Luminance: df=3,27 f=5.03  p=.007

Three way interaction:
- Scene x Location x Luminance: df=3,27 f=0.14  p=.932

Thus the effect of Luminance (increasing object luminance generally results in the moving object being positioned further from the observer) is highly significant, as its interaction with the target Location. This interaction is shown graphically in Figure 6.8, where it can be seen that the slope across luminance levels for the far location is much steeper than that for the near location, and covers a wider range of error scores.
Figure 6.9 shows the mean error scores, across subjects and target locations, plotted against absolute luminance values of the MO. It can be seen that the regression lines (regression of Y on X) have substantially differing slopes. The values of $r^2$ are 0.961 for the Dark set and 0.885 for the Light set. It can also be seen that there is a marked difference for the error scores for the two luminance values common to both sets.

The medium-light (93 cd/m²) and light (123 cd/m²) shadings for the dark set have effectively the same luminance values as the medium-dark (93 cd/m²) and medium-light (122 cd/m²) shadings for the light set. That observers place the moving object substantially further away in the dark scene set demonstrates that the positional error is influenced by the whole scene displayed, and not simply by object to background luminance contrast.
Figure 6.8: Interaction: Moving object luminance and target location.
Figure 6.9: Regression plot of light and dark scene sets.
4.4. Discussion.

In this experiment, the manipulations of object luminance have been shown to have similar effects on scenes with a moving object under observer control to those in static scenes with an adequate degree of perspective information: a brighter object is generally perceived as being nearer. If this object is required to be moved to a specific location, an increase in luminance will result in its being located further from the observer.

This effect was stronger for the far target location. Two possible explanations are offered for this, both relating to actual events on the screen. Firstly, as the MO moves further away, the size of the screen image reduces; information from linear perspective is still sufficient to specify a 3-D object, but a proportionately greater movement along the z-axis is required for a single pixel reduction in the displayed length of an edge. Given the finding in the previous study with regard to individual differences in depth perception, and the marked increase in the Standard Deviations for the rear target location, this explanation seems plausible. This could allow the luminance information to have a greater effect. Secondly, there is an actual increase in luminance as the MO passes from the front to the rear target position; this is the reverse of the centre to edge luminance fall-off. Although the actual movement on the screen is only 7% of the screen diagonal, the MO increases in luminance by between 4.8 cd/m² and 5.6 cd/m². Since this increase is near constant, one would expect a greater effect on the Dark scene set, and the mean error scores in Table 1 show that this is the case.
The general implication of these results is that it is not the absolute luminance value that has determined the location of the MO, but rather its luminance relative to the static scene components. In this study, the scene components do not offer single luminance and contrast gradients as did the first five studies. Rather, several such gradients were present: MO to background, MO to ground plane, and MO to the pyramid objects.

In the four steps through each set of MO shadings, the Michelson contrast with the ground plane reduces. Following the views of O'Shea et al. (1994) or Ross (1993), at the front target location, the MO is seen against the ground plane only, and a reduction in contrast should lead to the MO being further away. This should, in turn, have led to its being positioned nearer to the observer as the contrast decreased. As Table 6.3.1 shows, this did not happen at all with the dark MO set, and only between steps 2 and 3 with the light MO set. At this target location, contrast has not been as influential as luminance information.

At the rear target location, assessment of the contrast is somewhat complicated in that the MO is seen against both the ground plane and the "sky" background. Any adjustment in the MO position will alter the proportion of its area seen against each of these, and there is thus no simple formula for calculating the average contrast. This situation relates directly to normal simulator usage, where moving objects of other than rectangular shape (surface vehicles, ships, aircraft) are depicted against a constantly changing background. If the assumption is made that the MO to "sky" contrast
predominates, then the contrast ratio is lowest for step 2 in the dark scene set, and step 3 in the light scene set. Again, following O’Shea (1993) or Ross (1993), one would expect to find the MO positioned nearest to the observer for those two steps, whereas it can be seen from Table 1 that this did not occur. Similarly, if the MO to background contrast is assumed to be on a 50/50 weighting between ground and sky, the error scores obtained do not lend support to the views of O’Shea or Ross. Again, contrast has not been as influential as luminance information.

The next point to be considered is that of the luminance and contrast gradients between the MO and the pyramid features in the static scene. Here, the contrast ratio is always lowest at step 2, and increases through steps 3 and 4. At the front target location, the mean error scores do conform to this pattern and could be said to support the contrast theory; but, across these three steps, the luminance and contrast gradients are not in conflict. At the rear target location, there is no indication of the MO being placed nearer to the observers for step 2. On balance, therefore, there is more support for the luminance gradient having been influential in the judgements made, than for the contrast gradients.

4.5. Conclusion.

The results of this experiment are taken to confirm those of the first three experiments: where there is adequate information from linear perspective to specify the spatial layout...
of the scene, the luminance gradient across objects in the scene can moderate an observer's perception of that layout.

5. General discussion.

In Experiment 6, it was seen that the subjects' judgements of brightness tended to follow the size of the bright patches, rather than their actual luminance. Experiment 7 did not support either luminance or luminance contrast as cues to depth; rather, the relative change from the previous scene appeared to be influential. In each of these experiments, no other cues to depth were available in the stimuli, whilst the cues to the flatness of the display were present. Perspective and horizon information were available in Experiment 8, but with a moving object that did not, itself, offer any perspective information, it was the presence of object to background contrast, rather than the direction of such contrast, that was significant.

Only in Experiment 9, in which both the simulated landscape and the moving object were depicted in three dimensions, did changes in the luminance of the moving object have a significant influence on its position. Here, the results indicate that luminance gradients rather than luminance contrast gradients have had the larger effect on the positional judgements of the moving object. This is similar to the results for Experiment 3, where luminance gradient rather than luminance contrast gradient had proved to be influential.

The final chapter will discuss the full set of experiments and consider their implications.
1. Introduction.

In general terms, the experiments reported here have shown that luminance differences between objects in a scene can influence judgements of the spatial layout of that scene. The strength of that influence, and its direction, appear to be determined by the amount and type of other depth information available. The findings bear directly on a discussion of the relative functions of luminance (or brightness) and luminance contrast as cues to depth, and particularly on the statement by O'Shea, Blackburn and Ono (1994) that luminance is not a cue to depth. The way in which use is made of the cues available to an observer at any given time can be related to the models of Bruno and Cutting (1988) and Landy, Maloney and Young (1991).

2. An overview of the results.

The static-scene experiments.

Experiments 1 and 2 presented a line of three identically sized and equally spaced objects, and showed that:

a) differences in object luminance would affect the perceived layout, with the inter-object spacing appearing to be unequal.

b) the perceived change was measurable.

c) the manner in which the object luminances were ordered would affect the perceived change in inter-object spacing.
Both experiments used a light background, without any form of horizon being present. The perceived object shift was, in each case, consistent with the brighter object being seen as nearer, and not with the object offering the highest contrast being seen as nearer.

Experiments 3, 4 and 5, utilising a comparison task between two lines of objects (one a constant reference, and one variable) showed that:

a) the perceived spatial layout of the scene was generally influenced by the amount and type of depth information available.

b) the available information also specifically affected whether luminance differences or luminance contrast differences influenced the perceived spatial layout of the scene.

In Experiment 3, the line of objects ordered Light-Medium-Dark was generally perceived as being longer than the line ordered Dark-Medium-Light. As with the first two experiments, this suggests that luminance has influenced the judgements rather than luminance contrast. Removing the centre object from each line for Experiment 4 resulted in the two luminance orderings giving an equal percept of line length. Manipulating the height of the objects in the variable line, in Experiment 5, reversed the effect noted in Experiment 3: the line of objects ordered Dark-Medium-Light being generally seen as longer than the line ordered Light-Medium-Dark. Here, lower luminance contrast, not lower luminance, has indicated greater distance.
Brightness judgements.

Experiment 6 required observer judgements of the brightness of areas of a monitor screen, visible through apertures in a mask. The results showed that such judgements were generally influenced by the size of the aperture, rather than by the luminance of the screen area visible through the aperture.

The moving object experiments.

In these three experiments, the amount of perspective information available to observers was progressively increased. In Experiment 7, observers were shown a horizontal stimulus bar on one display and were required to match the width of this stimulus with an adjustable bar on another display. Here the subjects appeared to be following the change in total luminous energy from the display, rather than the change in luminance or luminance contrast, from one stimulus to another. No perspective information was available to the subjects, and the instructions referred to adjusting the size of the bar rather than its distance.

Experiment 8 did offer perspective information from the static components of the scene (two walls forming an alley), and the subjects were required to locate a two-dimensional bar level with each end of the alley. In this case, the presence or absence of bar-to-background contrast, rather than the direction of any luminance or luminance contrast gradient, was the only factor to have a significant influence on the location of the moving object. The effect of having luminance contrast between the moving object and
the background was that, in the far target location, the moving object was located farther from the observers.

Perspective information from the moving object was available in Experiment 9, and the increased number of static objects in the scene increased the amount of perspective information available. Here, the results suggest that the luminance gradient, rather than the luminance contrast gradient, influenced the adjustments made by the subjects. As the luminance of the moving object was increased, the moving object was positioned further from the observers. In this experiment, the moving object could be seen against the ground plane, the background, or both; there were, therefore, several luminance contrast gradients available. Separate luminance and luminance contrast gradients were available between the moving object and the static objects in the scene. Since the same luminance value for the moving object produced substantially different mean positions (see Figure 6.9 in the preceding chapter) in the light and dark static object sets, without any change in ground plane or background luminance values, the object to object gradients must have been used to arrive at a positional judgement. However, the difference in the slopes across the four values of moving object luminance for the two sets, argues that the gradient across objects was not solely responsible for the differences in the mean positions.

Taken overall, generic luminance differences between scene components have been shown to influence judgements of the spatial layout of that scene. Since luminance, and

210
luminance contrast, in the form of gradients across scene components, have each been shown to be a cue to depth or relative distance, it is not possible to exclude either from having an influence. Where one gradient has been available, so too has the other, and the relative influence of these two gradients as cues has been determined by the availability of other depth information. The manipulations in the total amount of depth information in Experiments 3 to 5 showed that either could have the greater influence. Similarly, the progressive increase in depth information from Experiment 7 to Experiment 9, indicates a need for other information to be available before either luminance or luminance contrast has a significant effect on positional judgements.


It was shown in Experiment 5 that the change from requiring subjects to judge the longer of two lines, to requiring them to judge the shorter line, produced significant differences in the accuracy of judgement of the relative lengths of the two lines of objects. Regardless of whether the instructions required the judgement of the longer or the shorter line, the task required a comparison between the two lines. Since the greatest variability occurred when the variable line was shorter than the comparison line (see Figure 4.10, Chapter 4), it may be assumed that seeking the 'shorter' line led to that group of subjects giving the non-luminance based information a higher weighting. This leads to a further point: Experiment 7 did not show any significant difference between luminance and luminance contrast, or indicate that either functioned as a depth cue in the absence of other information. The O’Shea, Blackburn and Ono (1994) study was fundamentally similar, yet obtained a clear finding that contrast functioned as a depth
cue. The operational differences between the two experiments lay in the method of obtaining subject response; O’Shea et al (1994) asking which foreground stimulus area appeared to be the nearer, while Experiment 6 here required a size adjustment. In asking for a judgement concerning depth, without offering other depth information, O’Shea et al (1994) may also have influenced their results by the nature of their instructions. This comment cannot apply to the work of Ross (1993), since her targets were at differing distances, and she required absolute distance judgements from her subjects.

4. **Cue combination and cue conflict.**

Given that so many theories of visual cognition accept that some form of weighting is applied to the available cues (Taylor, 1966a,b; Green and Stacey, 1966; Pressley, 1971; Bruno and Cutting, 1988; Landy, Maloney, Johnston and Young, 1991), it may appear superfluous to speak of cue conflict, since the weighting process, in whatever form, is the mechanism by which separate cues are combined, and conflicts are resolved. Assumptions that all the available information is processed, however, and that the available information is sufficient to produce the ‘right’ percept, may not be correct.

It was shown in Chapter 2 that a monitor screen can offer cues to the flatness of its surface, while depicting a scene offering cues to depth. The pilot in a flight simulator can clearly set aside some cues to flatness, along with the knowledge of being in a simulator, and attend only to the scene depicted as having depth. In this case, the
conflict can be handled very easily by simply not processing all the available information continually. Of more concern is conflict between depth cues in the depicted scene.

In the natural world, luminance gradients and luminance contrast gradients are normally negative, luminance and luminance contrast both reducing over distance due to atmospheric perspective. The comparison task experiments detailed in Chapter 3 offered opposing gradients, a negative luminance gradient also represented a positive luminance contrast gradient. Changes to the amount and type of other information also changed the dominance of one gradient over the other. Similarly, in the moving object experiments reported in the previous chapter, neither gradient had any significant effect until a substantial amount of other information became available (Experiment 9), and in this case, the scenes were sufficiently complex that more than one luminance gradient or luminance contrast gradient was present. Clearly, the weighting process for each cue takes into account the other information available, even if the definition of 'other information' is narrowed down to that from the depicted scene.

Bruno and Cutting (1988) stated clearly that some types of depth information might not be amenable to their simple additive (after weighting) model of cue combination. One model of cue combination that does allow for variations both in cue availability, and in the amount of information from each cue, is the two stage model proposed by Landy, Malony, Johnston and Young (1991). By evaluating (weighting) each cue in isolation, and then re-evaluating by comparison with each of the other (weighted) cues the
maximum use is made of the available information. The Landy et al (1991) model is effectively a form of parallel processing, which is consistent with the multi-channel, parallel processing view of the brain (Pohl, 1973; Livingstone and Hubel, 1989; Rybak, 1993; Eiser, 1994). Such a model would explain the results obtained in Experiments 3 to 5.

5. The immediate implications.

In their review of the literature on simulator image quality, Padmos and Milders (1992) have focused on the degree of detail, and the type of information necessary for the satisfactory performance of a wide range of simulated tasks. Matters of cue combination and cue conflict were not directly raised, although dependence of the need to provide one cue on the availability and strength of others, is acknowledged. Padmos and Milders (1992b) also comment that it is difficult to generalise across the published data on a specific cue.

It seems clear that conflict between the luminance gradient cue and the luminance contrast gradient cue, within a simulator display, can lead to an inappropriate percept of the depicted scene. The results obtained here support the view that the effect of one cue depends on the presence and strength of others, and can be explained by the two stage cue combination model proposed by Landy, Malony, Johnston and Young (1991). Experiments 3, 4 and 5, using identical luminance and luminance contrast gradients, and identical tasks, have shown how the type and amount of other information can affect the
results, to the point where luminance appears to have influenced percepts of spatial layout in one case, and luminance contrast has been influential in another. Given the increasing use of simulators, for a growing number of applications, cue conflict should be added to the list of factors to be taken into account when a simulator system is being designed, or evaluated.

In part, the findings have been influenced by the measures used: in the case of Experiments 3, 4 and 5, the question of the number of times the variable line of objects was judged to be longer than the comparison line. Whether accuracy of judgement is more, or less, important than the direction of any error must depend on the type of simulator and the task it is intended to simulate. Transforming the scores in the three comparison task experiments to show the accuracy of judgement, would show the negative luminance gradient (Light-Medium-Dark) consistently giving more correct judgements than the negative luminance contrast gradient (Dark-Medium-Light). Such a transformation would not have revealed that both gradients led to those variable lines of objects being seen as longer than the comparison line when they were, in fact, shorter. These three experiments make an interesting contrast with the work of Baird (1992), who required judgements as to which of two targets was the nearer, and using reaction times and correct judgements as measures.

Baird's (1992) finding that brightness cueing - giving the nearer target a higher luminance value - produced the lowest error scores, and the shortest reaction times,
could be said to support the results of the three comparison task experiments here. However, to generalise further without any indication of the apparent distance between her two targets, would be unsafe, giving emphasis to the point made above by Padmos and Milders (1992).

It should also be noted that Baird (1992) aimed her research at head down and virtual cockpit displays, and was certainly aware that increasing the complexity of the display could in turn influence percepts of the scene displayed. Improvements in computer and display technology occur at such a rate that long-term implications drawn from the research here may subsequently prove to have a short life. Thus, the general finding that *luminance differences between objects can affect perception of their spatial layout*, and the specific finding that the *amount and type of other information in the scene will determine whether luminance gradient or luminance contrast gradient will moderate perspective information*, must be set against knowledge of a specific simulator display, and the task for which that simulator is being used.

There is a second aspect to the rate of technological advance: while the "latest and best" is usually the focus of attention, yesterday's best becomes tomorrow's basic model, available at far lower cost, and applied to tasks that the original developers did not contemplate. The ability to produce scenes with correct linear perspective (but without real-time animation) is now available on a personal computer to designers and salesmen.
in the fitted kitchen industry. It can only be a matter of time before manipulation of the surface luminance values, to enhance the feeling of space, becomes a sales technique.


Theoretical

The two stage, weighted-additive model of cue combination, Landy, Malony and Young (1991), clearly warrants further research. This could well be done by extending the method used here in Experiment 7: that of matching a response bar for size with a stimulus bar. Increments in the amount and type of information could be made by depicting the bars in three dimensions, adding ground plane and horizon, ground plane texture, other objects to the scene, creating shadows for the bars, et cetera, whilst retaining the luminance and contrast manipulations. A second line of approach could involve using three-dimensioned bars with the luminance and contrast variations, and a series of changes in the proportions of the bars so that the major dimension changed from the y to the z axis. This would bear directly on the influence of linear perspective. Either approach would require equipment with similar capabilities to the BEST, particularly with respect to the ability to log a large amount of co-ordinate data. Given suitable software, such research could probably now be carried out with a powerful PC, which would reduce the time taken in downloading data-log files (see Appendix 1).

Another area that may be due for more attention is that of the way in which the luminance contrast ratio is calculated. In this work, all luminance contrasts specified
have been calculated as Michelson contrasts: the difference in luminance between two areas (normally foreground and background) divided by their sum. This is not the only method used; Ross (1993) used the difference divided by the background, and Padmos and Milders (1992) have suggested the difference between adjacent areas divided by the mean luminance. Each method has limitations, and the use of different formulae can pose problems when comparing several research reports.

Consider a totally black foreground and a background of any value, or the reverse; the Michelson contrast ratios will be zero in either case, while the method used by Ross (1993) will give ratios of -1 or the value of the foreground. The formula proposed by Padmos and Milders may appear better suited to complex scenes presented on a monitor, but even in scenes no more complex than those used in some of the experiments here, would produce a large array of contrast ratios, and these would change if one scene component moved. A standardised method for calculating luminance contrast ratios on simulator displays must take into account the effect of centre-to-edge luminance reduction, and that the gradient across non-contiguous areas may also be relevant to any research findings.

Applied.

The practical effect of inherent luminance reduction, from the centre of the monitor screen to the edge, clearly needs investigating. This could be approached using methods similar to those of Experiments 3 to 5, with a mix of screen centre and screen edge
locations for the lines of objects. Since the scenes are static, scene generation could now be done using suitable software on a powerful PC fitted with a video frame-grabber. A subsequent step would be to apply any findings to events at those locations where a multi-channel projected display changes from one channel to another.

Other possible research areas would probably require access to an appropriate simulator system. In combat simulators - air to air, or ground to ground - the luminance or luminance contrast gradients across multiple targets may well influence judgements of their relative distance and thus influence the choice of target to be engaged first. A driver behaviour simulator could be used to investigate judgements of the speed of oncoming vehicles, particularly where there are multiple vehicles in an overtaking situation. The practical limits can only be defined in terms of equipment availability, and the ease with which manipulations can be made to the display, and data obtained from the system.

7. Conclusion.

The work reported here has shown that luminance differences between the objects in a scene, displayed on a monitor, will influence perceptions of the spatial layout of that scene. Rather than resolving arguments as to whether luminance or luminance contrast is a cue to depth, the results suggest that it is the luminance gradients, or luminance
contrast gradients, that operate as depth cues, with their effect influenced by the amount and type of other information available.

The interaction of different types of depth information can be explained in terms of an information-weighting model, processing the items of information in parallel; with simulator displays offering reduced information relative to the natural world, the inter-cue weighting may lead to percepts of spatial layout other than those that the equipment designers intended. The results preclude any conclusion of the type: Variation in cue A will lead to variation in percept B; rather, they suggest that to better understand the way in which cue A influences, and is influenced by, the other cues in a display, it is first necessary to clearly establish the strength of each cue. Simulator manufacturers are now focusing on the problem of applying 'realistic' texture gradients to their displays. While this will 'improve' the percept of depth, measurement of the 'improvement' will first require a valid measure of the strength of a texture gradient as an isolated depth cue, so that its interaction with other depth cues can be assessed. No cue is an island unto itself.
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232

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APPENDIX 1: The BEST Simulators.

These pieces of equipment were built by Akebia Ltd. (now Primary Vision Ltd.) to a Ministry of Defence specification, two being made available for research purposes by the Army Personnel Research Establishment. Much of the specification is not relevant to the research reported in this thesis, and will not be referred to here.

The BEST is based on a Force single-board computer, using the Motorola 68020 processor chip (making the basic system comparable to an Apple Macintosh II), mounted in a VME-Eurobus 19" industrial rack mount enclosure. Akebia produced the graphics processor board, system and graphics memory boards, and the control circuitry. A PAL encoder enables online video-recording of the graphics output. The operating system is Force P-Dos, which is generally similar to UNIX. One hard disk and one 3.5" floppy disk drive are fitted. Programming and system control are handled via a standard ICL 6402 character display terminal with remote keyboard. This part of the system can be seen as a single-user mini-computer, with dedicated graphics components.

Graphics output passes to a high resolution 13" RGB colour display monitor (.28mm dot pitch) displaying 570 pixels by 510 lines. Each colour signal and the synchronisation signal pass through separate low-loss co-axial cables to minimise cross-talk between channels. The monitor is equipped with a manual degaussing control.
Control of the graphic image is by a separate console, connected to both the main processor board, and the graphics processor. Amongst the functions available from the console are:

**Selection of eye position.** Up to 16 stationpoints can be defined, and repeated depressions of the "View" button will step through these following a programmable sequence.

**Selection of colour palette.** Up to 4 palettes, each offering 256 colours can be defined, and repeated depressions of the "Palette Change" button will step through these following a programmable sequence.

**Data log.** If this function is enabled during programming, depression of the "Log" button records the position of each scene component. Sampling can be defined for intervals from 50ms upward. The use of the "Log" button places a flag in the data file entry for the eye position at the time of button depression. The log-data file produced is standard ASCII text format, enabling downloading to an IBM-PC for subsequent processing.

**Moving object z-axis control.** A single axis proportional joystick enables movement of a pre-defined moving object (this could be an eye position, or a scene component object) along the z-axis of the scene. This function was used in Experiments 7, 8 and 9, at real-time animation speed (this is 60 frames/sec screen update rate).
Programming the BEST takes the form of constructing a database, within an application program written by Akebia Ltd. The procedure is to define all unique apices in a Vertex Table using x-y-z coordinates, and then to specify the apices for each polygon in a Face Table. The polygons can then be assigned a colour from the Colour Look-up Table. Colours are specified by setting the intensity of each of the Red, Blue and Green colour guns in the display monitor within a range of 256 steps (8 bits per colour gun), so that any colour palette can contain 256 colours from a range of 16.2 million colours. This enables good control over hue, saturation and lightness, but the colour gun response is near-logarithmic so that equal increments in gun value do not give equal increments in displayed colour. In practice this can prevent a specific luminance value being obtained (see Experiment 7). Only one colour from the Colour Look-up Table can be assigned to any polygon, although this can have different RGB values in each of the colour palettes.

Polygons can be linked together to make an object capable of movement, and those polygons which can not be seen from the eye position - e.g. the base of an object resting on the ground plane - need not be specified. This minimises the load on the main and graphics processors, so that a displayed scene can contain several hundred polygons without reducing the screen update rate. None of the experiments involving a moving object used more than forty polygons, and thus were not influenced by update rate reductions.
It can be seen from the above that the BEST was, in general terms, an appropriate piece of equipment for the research reported here. The data log capability did, however, have one serious limitation: data log files could not be downloaded at a rate greater than 1200 baud. In Experiment 7, a single session for one subject could generate a data file of between 350 Kb and 1.1 Mb; this used up hard disk capacity on the BEST quite rapidly, and required much time to download to a PC. In practice, no more than four subject sessions could be run without a break running into hours, in order to download the log files, and thus retrieve hard disk space on the BEST. Experiments 8 and 9 tended toward shorter sessions, and this limitation did not present any practical problems.