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MOVING MENTAL IMAGES ACROSS THE VISUAL FIELD

BY

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Moving Mental Images Across the Visual Field," submitted by Peter Roy Ballantine in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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Dedicated to C.H.B.

ABSTRACT

To explain Finke and Kosslyn's (1980) finding of reduced peripheral acuity in mental images within Kosslyn's (1980) imagery model requires certain assumptions about the nature of the imaging substrate. In particular, assumptions need to be made about the effective grain size of the medium and the allocation of processing resources to different areas of the image. These assumptions are each testable, and provide a means of testing Kosslyn's model in particular, and more generally, of testing spatial models of image representation as against the propositional approach. Three experiments were performed and the data from a fourth were reanalyzed to test these assumptions.

In the first experiment, 18 subjects imagined rigid arrays of points, and tracked an imaginary dot moving between the points. The time to imagine the inter-point passage was longer for those trials where the most eccentric points in the array were around 7 degrees from the tracked dot, than when they were 12 degrees from the dot. In the second and third experiments, different groups of 18 subjects imagined small objects to move at different degrees of

eccentricity from the fixation point in an otherwise stationary scene. In both cases, there was a significant quadratic effect of eccentricity in that the time required to imagine the move was greatest around 7 degrees of eccentricity, and less both nearer and further from the fixation point. Finally, Jol[illegible] and Kosslyn's (1985) map scanning data were reanalyzed in terms of the relative eccentricity of the points on the map during each scan. The same quadratic effect was found.

The data are interpreted as providing evidence against a propositional model in favor of an elaboration of Kosslyn's model. A model is described in which image updating resources are allocated equally across the image, and in which the image substrate grain size is finest in the center and courser in the periphery.

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CHAPTER 1: INTRODUCTION

For most people, mental images seem highly similar to visual experiences. Imagined shape, size and color seem to take the same form in images as in the visual world, and so it is unsurprising that considerable evidence has been amassed to demonstrate such similarities (see Finke, 1980, for a review). In particular, the work of Shepard and his colleagues (see Shepard and Cooper, 1982, for a review) and of Kosslyn and his colleagues (see Kosslyn, 1980, for a review) has suggested that mental images are in some ways isomorphic to what is being imagined. Thus, for example, the time taken to imagine objects to move in an image, or to move the mental fixation point in an image, is a function of the distance moved. As a result of these and other findings, Kosslyn and Shwartz (1977), and Kosslyn (1980, 1981, 1983) developed a model of image representation in which size, distance and location are directly preserved in an active mental image.

Kosslyn's model accounts for a great deal of the data, but there are a few untested assumptions in the model, which this thesis addresses directly. In this chapter I will discuss those aspects of Kosslyn's model that relate to the characteristics of the substrate upon which images are purported to be depicted, and the issue of the apparent reduced acuity for parts of images located at the periphery of the image. I will concentrate on the alternative explanations for the phenomenon. In Chapter 2 I will elaborate upon the testable consequences of those alternative explanations, and show how image processing time can be used to support one or other of the approaches.

In Chapter 3, the testable implications of the different explanations for reduced peripheral image acuity are expressed in six hypotheses, and the details of the experiments run to test those hypotheses, and the results obtained, are provided. Finally, in Chapter 4 the results are discussed, as well as their implications for the explanation of reduced peripheral image acuity and for imagery theory in general.

Kosslyn's Model and Reduced Peripheral Image Acuity

Kosslyn (1980) argues that visual information is stored in long term memory in both propositional data structures and separate lists of data describing the distances and angles between parts of the image. Images are created by using this long term memory information to activate cells in a structure which he calls the visual buffer. The visual buffer is, functionally, a two dimensional matrix and so preserves the (two dimensional) structure of an imagined scene in a way analogous to a CRT or a TV screen. Distance across the imagined scene is therefore reflected in distance across the visual buffer.

Kosslyn (1980, p. 272) considers that in ordinary vision the visible world is most probably mapped onto the same buffer, and that the processes used to extract information from images and visual scenes are probably the same. This would account for the numerous parallels between vision and imagery, such as the findings that images and vision are confusable (e.g., Perky, 1910), have similar effects on motor behavior (Finke, 1979), are subject to similar illusions (Wallace, 1984), and are subject to other central effects like the McCollough effect and the oblique effect (Kosslyn, 1983, p. 82).

There are four characteristics of Kosslyn's visual buffer which are important to this discussion. First, Kosslyn states that the visual buffer "functions as a coordinate space. Information is represented in this space by selectively filling in local regions to depict portions of the represented object or objects"

(Kosslyn, 1980, p. 139). These local regions are like pixels on a CRT. Second, Kosslyn notes (p. 139) that the buffer has limited extent. This accounts for the finding that there appears to be a limit to the maximum size an object can be imagined (Kosslyn, 1978). Third, he states (p. 141) that images begin to fade as soon as they are created, and need to be regularly refreshed. This refreshing is not done by re-accessing the long term memory data but by somehow scanning across the image to the fading data (p. 150, p. 251). Finally, Kosslyn argues (p. 140) that the buffer has a grain size, such that information is unavailable when objects are imagined too small, and this grain size gets larger towards the periphery of the buffer. This property accounts for Finke and Kosslyn's (1980) finding that people are less able to resolve detail in the periphery of their images than in the center, which may be likened to reduced visual acuity in the periphery of the retina.

The CRT model is a convenient one, but it should not be taken too literally. The similarities between a CRT and Kosslyn's model include, for example, the fact that Kosslyn views the image buffer as a limited size functional matrix in which short-lived points depict imagined objects, just like pixels on a CRT.

Furthermore, in Kosslyn's model the depicted location of specific objects, or parts of objects, may be altered by "transferring" the points incrementally across the buffer in just the same way that one would depict movement on a CRT.

On the other hand, unlike when viewing a CRT, one cannot examine the details of objects on the edge of the image buffer directly, the way one can look at the side of a CRT screen. This is because the periphery of the image is, by definition, peripheral to the "focussed" area of the mental image, and, furthermore, according to the model it has a large grain size, or low resolution. To examine a particular peripheral object, or to "track" an object as it moves across the imagined scene, the whole image has to be moved across the buffer so as to bring the object of interest, or the moving point, into the center. Kosslyn (1980) calls this a "field general" transformation. From the perspective of the imager, the effect of moving the image across the buffer in this way is similar to the effect of scanning the eyes across a visual scene to bring previously peripheral visual material across the retina to the fovea. Since the two are functionally equivalent, the expression "scanning" across the image is used in Kosslyn's work and in this dissertation.

even though it is by no means implied that scanned material remains stationary while the scanner moves.

Kosslyn's (1980, pp. 139-141) conclusions about the reasons for, and mechanism of, reduced acuity in the periphery is the focus of this thesis. The major evidence for this position stems from a study by Finke and Kosslyn (1980). In that study, subjects were shown a pair of dots separated by a small gap. The subjects were then asked to look at, or imagine looking at, the dots on a screen, and then scan their eyes slowly away in a horizontal or vertical direction until they reached the point at which they were unable to resolve the two points. By plotting these resolution boundaries, and systematically varying the dot separation, Finke and Kosslyn were able to map the fields of resolution for different dot separations.

Finke and Kosslyn's finding was that image acuity, like visual acuity, falls off monotonically as one moves out from the center, and furthermore, that the shape of the fields of resolution is the same (i.e. oval, and extending further below than above the fixation point) for both modalities. This latter finding is particularly important because there is little doubt that most subjects would know that visual acuity is better at the fixation point, and so could easily reproduce a simple decreasing acuity function in their images. The subjects in Finke and Kosslyn's experiment, however, did not predict the shape of the fields of resolution which was shared by the two modalities. The study is, therefore, relatively immune to Pylyshyn's (1981) "tacit knowledge" attack, that any consistency between subjects was due not to the operation of postulated mental mechanisms, but to their shared tacit knowledge of the laws of physics.

Kosslyn (1980) notes that the visual buffer could have a grain size which is constant throughout, and the reduced acuity could then be obtained if the procedures operating on the buffer allocated more resources to the more central area. Alternatively, the reduced resolution could be due to structural limitations, such as larger grain in the periphery. Kosslyn points out that when (if) the buffer is used to represent visual percepts the resolving power of any given part of the buffer need be no greater than the resolving power of the associated part of the retina. According to this view, small grain size in the periphery of the buffer is redundant during visual activity and so it does not exist. Thus, for reasons of "explanatory adequacy and computational ease" (p. 140), in Kosslyn's model the peripheral buffer cells account for a larger visual angle per cell than do the more central cells. In his simulation Kosslyn uses only two levels of grain size (see for example Kosslyn, 1980 p. 147) but his discussion of the model (p. 140) and the results of Finke and Kosslyn's (1980) study clearly suggest a continuous gradient of resolving power.

Kosslyn acknowledges that his choice of a structural rather than procedural explanation is somewhat arbitrary (1980, pp. 139-140), and that the question is empirically answerable, but he nevertheless left the assumption untested. The structural versus procedural alternatives are examined in more detail below, and some of the implications of each are mentioned.

The Structural Explanation

The structural explanation of Finke and Kosslyn's (1980) finding of reduced acuity for images in the periphery of the visual buffer is that the "receptive field" of the cells in the peripheral area of the visual buffer cover a wider visual or imaginal angle than more central cells. The theory is that if two points are mapped onto the central part of the buffer with one or more empty buffer cells between them, the points will be distinguishable. If the same two points are imagined to move towards the periphery they will eventually fall into the same or immediately adjacent cells and thus become indistinguishable from one another.

A question that arises from this concept of the buffer is how the missing detail in the periphery is recovered when the imager scans across the image. Scanning across the image brings previously peripheral and, therefore, incompletely resolved information, into the central, highly resolved area. Kosslyn explains the appearance of the previously absent information by reference to a general purpose operator called the "inverse mapping function." This function provides for rapid access to the long term memory structures relating to the contents of each cell. Where more than one point is mapped onto a single cell, that cell is "marked" and the imager may then use the inverse mapping function to rapidly resolve the missing detail when it is brought into an area of higher resolution.

A point which Kosslyn does not mention, but which is implied by the idea of a varied grain size image buffer, is that shifting the image across the substrate, such as when scanning across the image, also requires something like an inverse mapping function to prevent the image from becoming distorted. For example, consider a case in which the image is being shifted to the left. If in a given cycle the imager moves all parts of the image one cell to the left, then each part of the image will appear to have moved left by an amount equal to the visual angle separation between the cell that the part started on, and the adjacent cell that it ended on. According to Kosslyn's theory the visual angle accounted for by peripheral cells is greater than the central cells, and so peripheral parts of the image would have moved through a greater visual angle. The image would therefore be slightly distorted during the move, and would become more distorted during each subsequent move. Under a varied image buffer grain size model, therefore, some additional function beyond Kosslyn's inverse mapping function is needed to determine whether each cell depicting the location of a peripheral and incompletely resolved part of the image needs to be updated during a particular cycle, or not.

A consequence of varied grain size is, therefore, that moving objects inwards from the periphery of the image buffer necessitates repeated use of the inverse mapping function to fill in missing detail, whereas moving the same object within the central, completely resolved region does not. Such repetitive memory access presumably takes time and should therefore affect transformation speed, irrespective of whether the transformation is the movement of the whole image such as when scanning the image, or the movement of only parts of the image, such as when imagining moving and stationary objects simultaneously (Kosslyn calls these "region bounded" transformations). Transformation speed thus becomes a test of the existence of such extra processes in peripheral transformations as compared to central transformations.

In creating an image of a given scene the imager selects a level of resolution which is appropriate to the task. This point is important in the interpretation of my results and so I shall give it special attention. Subjectively, one can imagine objects at a given distance, without "seeing" all of the detail which could be detected at that distance. For example, one can imagine a car at a distance of, say, 30 feet without necessarily including all of the detail in the image that one could see at such as a distance. For example the image would not necessarily include the door handle, the shape of the back window, or the profile of the driver, if those details did not contribute to the purpose for which one had created the image. One can, of course, rapidly fill in any details needed. The purpose of limiting resolution would be to limit the processing effort required to create the image, and the effort required to transform it since there are fewer data in a low resolution image.

According to Kosslyn's model, a given small element in an image is either fully resolved at the selected level of resolution and has no need of the inverse mapping function during scanning (such as when it is near the center), or it is not fully resolved. If the element is not fully resolved it is in an area of the buffer where buffer's resolving power is unable to resolve the fullest level of detail desired. Kosslyn introduced the term "overprinted" in this context because in his simulation two separate data points in one cell would be printed on top of one another. Such elements require the use of the inverse mapping function to resolve the missing detail when they are moved inward.

Kosslyn does not suggest that objects are only fully resolved at the very center of the image, since that would mean that changes in resolution are only possible through "zooming in," but rather, that objects near to the focus point can be resolved at the chosen level of resolution. This means that for a given level of resolution there is an area in the center of the image buffer where the resolving power of the buffer is not fully utilized, irrespective of the size of the particular objects represented there. When the level of resolution used is high then this area would be small, and vice versa.

It follows from the above that if a fully resolved, non-central object is moved inwards in the image, then that object is moving into an area of finer grain, without gaining in resolution even though resolution improvements are possible. The inverse mapping function, or whatever is responsible for adding detail as objects become better resolved, therefore ceases to operate in the fully resolved region, unless one decides to change the level of resolution, and add more detail (this is not to say that other special procedures are not required). This has important implications. If the inverse mapping function is not used when scanning in the central region, and is used in the peripheral regions, then one might expect a disjunction in the transformation speed function at the point where the object becomes fully resolved. The latter point will be taken up in more detail in the chapters to follow.

The Process/Procedure Explanation

Finke and Kosslyn's (1980) reduced peripheral acuity effect can also be obtained by means of special, eccentricity-dependent processes working on a buffer, which has constant grain size, rather than the systematically varied grain sizes that Kosslyn (1980) proposes. The "image inspecting" operators may merely operate in a more gross fashion in the peripheral area. That is, when working in the periphery the operators may report the location of a given element less accurately, or at a lower resolution, even though the actual resolution is constant.

In a buffer with a constant cell size it would be easier to move the image back and forth without distortions occurring and without the necessity for an inverse mapping function. This is because a simple move of each point to an adjacent cell is all that is required. The time taken to accomplish a given linear transformation would therefore be proportional to the absolute distance traversed only, and unrelated to the eccentricity of the transformation. A constant grain size approach is simple, efficient, and consistent with the literature. It has its limitations, however.

One problem with this approach is that image rotation is more difficult to accomplish in a constant grain substrate. This is because more eccentric parts of an imagined rotating object cover a greater length of arc in unit time than do central parts of the same object. To prevent the object from becoming twisted during such imagined movements the image moving operators would therefore have to move eccentric parts further, in terms of visual angle per cycle, than central objects. In the case of the varied grain size approach, since eccentric cells account for greater visual angles, no special procedures need be required. That is, if the image grain size is proportional to eccentricity in the same way that the resolving power of the eye is (Drasdo, 1977) then a one-cell rotary movement at any level of eccentricity will correspond to the same angular change as measured from the fixation point. In the case of constant grain size the image rotating operators would have to move the eccentric parts of the image across a number of intervening cells for every one-cell move in the center. This extra processing should be reflected in the time required to accomplish rotary transformations, and so again transformation time will provide useful data in deciding between these alternatives.

The implications for transformation speed of the varied versus constant grain size approaches are clearly different. Specifically, with varied grain size one would expect radial linear transformation times (transformations inward or outward from the center) to vary with eccentricity, whereas they should be constant under the constant grain size model. Of course one could argue that the grain size _is_ constant but that the transformation operators work more rapidly or efficiently at the center than at the periphery for linear transformations, and vice versa for rotary transformations. Under such a system, however, it would be impossible to scan a large image without the image becoming distorted, since at any one time some parts of the image are more peripheral than others and so would be moved at different speeds. Furthermore, an inverse mapping process is still required in a constant grain size model to allow image enlarging ("zooming" in Kosslyn's terms) and to update the edges of the buffer as one scans continuously in a given direction (the purpose for which Kosslyn originally invented the concept). In conclusion, therefore, although both approaches have their merits, the varied grain size approach seems to require fewer assumptions.

CHAPTER 2: THE SPEED OF PERIPHERAL PROCESSING

This chapter is in four sections. In the first two sections examine the consequences, and the merits and demerits of models which hold that processing resources are allocated equally to all cells of the image buffer but that the grain of the image buffer is either a constant size throughout, or that the grain size is varied. In the last two sections I will examine the effect of differential resource allocation.

The Varied Grain Size Approach

The following section is an analysis of the implications of a model which holds that the grain size of the visual buffer is graded (either continuously or in steps) and that all parts of the image are serviced (refreshed or updated) equally frequently. This is <u>not</u> to say that I assume all buffer cells are given equal time, merely equally frequent attention irrespective of the relative amount of time it may take to service each cell.

Figure 1 provides an illustration of a varied grain size buffer with a number of objects marked on it. The numerals in the figure identify hypothetical

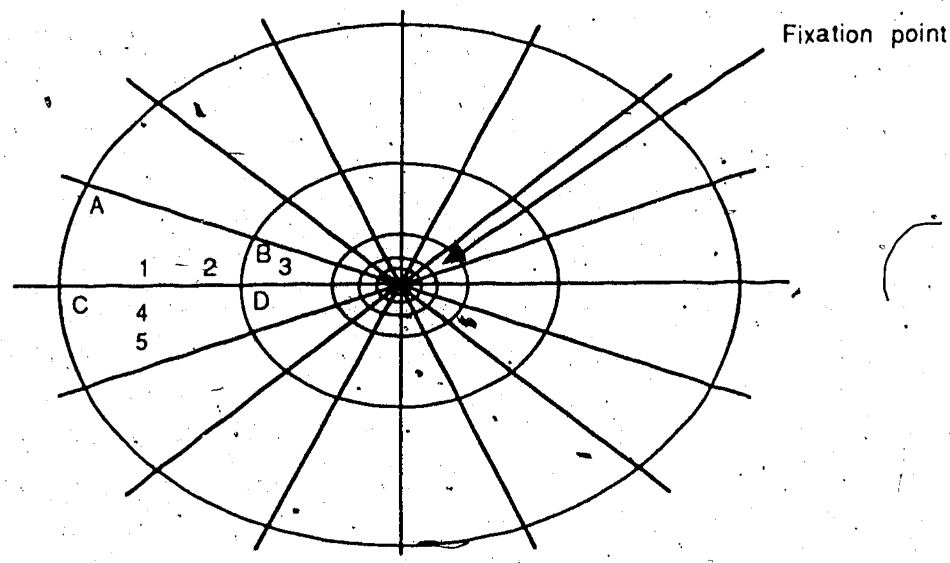

Figure 1. A schematic representation of the varied grain size image buffer.

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objects, or different parts of a complex object. The letters in the cells will be used to identify particular cells. It should be noted that the cell <u>size</u> in the illustration represents the size of the visual angle accounted for by each cell, and not the size of the cell itself. Thus, for example, objects 1, 2 and 3 are imagined to be equidistant even though the three objects are represented in only two cells. On the other hand the separation between objects 1 and 2 in the figure could not be immediately inferred from such an image, since in Kosslyn's model each cell can only signal the presence of an object or objects "somewhere" in the area that cell accounts for.

In moving an image of some small object (or an element of a large one) a number of possibilities exist. Consider an object in the periphery which is smaller than the visual angle of a peripheral buffer cell, such as the 2 in Cell A of Figure 1. If this object is imagined to move a small amount towards the center of the image, then a number of different things could be happen. Three of them are discussed in detail in the paragraphs to follow.

The first way in which the buffer could be updated is that the contents of each buffer cell could be transferred in total, without reference to what is represented. The 1 and the 2 would therefore be moved into Cell B. The second possibility is that, if the cell is marked as overprinted, as would be the case in the case of the Cell A the contents of the cell could be checked by means of some local or long term memory process to see if the object should occupy two cells after the move, and then moved to the next cell or cells as appropriate. Note that in both of the above approaches the cell representing an object is always checked and changed on every cycle.

A third possibility is that the precise location in the real world of the represented object could first be checked. Since the cell accounts for a finite visual angle, it may be the case that the object, after moving, still falls in the region covered by the original cell (such as object 1 after a small movement of that object to the right), in which case the cell would not be changed. If the object has reached the boundary of the region covered by the first cell it could then be moved (with possibly another reference to long term memory to handle overprinting).

Because the peripheral cells account for greater visual angles than the central ones, a one-cell increment in the periphery is associated with a greater real-world distance than a one cell increment in the center. Under the first option above, in which the total cell contents are transferred in each cycle, this would mean that a small object (such as object 1 on its own in Figure 1) which is being moved from cell to cell at a regular rate across the image would appear to cover a greater distance in unit time at the periphery than at the center. That is, the rate of movement of that object would decrease towards the center.

When an object is in the periphery it is likely to be overprinted (such as objects 4 and 5 in the figure). Under the second option above, (in which the processor checks for overprinting before effecting a move), a one step move of these two objects towards the center would require long term memory access to check if the objects should be represented by two cells after the move. If the object does not need to be further resolved then the move is performed and the object is transferred to the next cell (both 4 and 5 would be transferred to cell C). The size of the resulting imagined real-world movement will depend on the size of the cell and so, again, the object will be moved over greater visual angles each time the cell is updated in the periphery than in less peripheral locations. The rate of movement would thus decrease as an object moved towards the center since more cell moves are required per degree of visual angle. Once the object is in the fully resolved area of the buffer and no overprinting exists, then long term memory access is no longer needed and the cell representing the object's location can be updated much more rapidly. The object will still cover less visual angle per cycle as it moves towards the center, however, because of the ever decreasing amount of visual angle covered by each cell.

Thus, under the "check for overprinting" option the movement rate ought to decrease towards the center and there should be a disjunction and relative increase in processing speed at the point where the object becomes fully resolved.

The problem with both of the above approaches is apparent if one considers the case of two separated objects such as points 1 and 3 in Figure 1 moving together across the buffer. Since the visual angle traversed per cycle is a function of the eccentricity, and since at any moment the two objects will have different levels of eccentricity, the real world distance between them would change as they moved. Generalizing this effect to more complex objects, it is clear that objects would become distorted as they were scanned across the image substrate. On the other hand, this movement speed disparity would be an advantage in the case of mental rotation of objects in the picture plane about the center of the image because, in the real world, peripheral parts of a rotating object do move further than central parts for a given angle of rotation.

The third image transforming process option above is similar to the "check for overprinting" option, except that the precise location of the object in imagined visual space is checked prior to each incremental move. If the object's new location after the move would fall outside the range of reference of the original cell then it would be moved to the new cell; otherwise it would remain in the original cell. This would eliminate the problem of size or distance distortion which otherwise results from the varied cell size since objects are not necessarily transferred on every cycle. Nevertheless, as the object moves in from the extreme periphery the processor will have to update the cell in which the object is located more and more frequently while still using the inverse mapping process on every cycle -- requiring more work per unit distance. The result would be that moving a single and incompletely resolved object over a given visual angle would take less time in the extreme periphery than in less peripheral areas. Once the object is resolved (at the chosen level of resolution) the long term memory access is no longer needed, and so the effort required per cycle is reduced, which could decrease the time required to affect a given movement. This third option therefore permits complex objects to be moved without size and shape distortion, and does not waste processing effort on fully resolved objects. On the other hand, the time required to accomplish a given visual angle movement would still not be constant at all levels of eccentricity.

Those transformations which are at right angles to the radii of the buffer (such as if objects 4 and 5 move vertically) I will call "tangential" transformations. Tangential transformations over short distances do not require changes in resolution (since the object remains approximately the same distance from the center throughout). Nevertheless the effect of the larger cell size at the periphery will be the same for these transformations as for the radial transformations discussed in the previous paragraphs. The time taken to traverse a given distance will therefore be less for more peripheral tangential transformations than more central ones.

The common theme in each of the above descriptions is the point that the varied grain size model implies more processing effort per degree of visual angle moved in the center of the buffer than the periphery. In addition, the idea that objects are not fully resolved in the periphery but become fully resolved in the center implies some kind of disjunction in processing effort at the point where the object becomes fully resolved. As a result a plot of processing time (y axis) against eccentricity (x axis) would show a sawtooth function -- initially decreasing, a disjunction and relative increase, followed by more downslope as one moves out to the periphery.

Since Kosslyn opted for a graded grain size approach one might ask how he accounted for the above issues. First, he (Kosslyn, 1980, p. 165) admits that he is "not in a position to offer seriously a theory of mental transformations." He chose this approach over the constant grain size approach on the grounds that (p. 140) (a) the varied grain size approach makes it easy to explain the fall off in resolution reported by Finke and Kosslyn (1980), (b) it is easier to justify or explain a buffer in which the resolving power matches the resolving power of the associated parts of the retina (c) and the varied grain size approach is in <u>some</u> respects computationally easier.

In his actual simulation Kosslyn avoided the consequences of varied grain size by, in fact, using a constant grain size. That is, in his simulation, Kosslyn (1980, p. 140) used a constant cell size buffer, but filled in only one randomly chosen cell out of every group of nine in the periphery. This, he argued, gives a larger "functional cell size" (visual angle) in the periphery while eliminating all of the computational problems which a true simulation of varied grain size would have. In the simulation, transformations were performed by simple incremental movements across equal distances in all parts of the buffer (which is not possible if the grain size really is varied), and only after the move had been completed was the resolution adjusted. Thus, while Kosslyn argues for a varied grain size, his simulation used a constant grain size.

The Constant Grain Size Approach

The following section is an analysis of the implications of a model which holds that the grain size of the visual buffer is constant throughout, and that all parts of the image are serviced equally frequently. As mentioned previously, constant grain size has the advantage that all regular incremental transformations require the same processing effort, irrespective of where they occur. Thus a movement over unit distance of a small object will take the same time irrespective of where in the image buffer it occurs. Rotary movements and movements at a tangent to the diameter of the buffer should, technically, be the same as all other movements. However, as discussed previously there may be some operator which serves to slow the movement of more central parts of a rotating object so as to prevent distortion.

The reduced acuity which Finke and Kosslyn (1980) found at the periphery of the image could be obtained by having the operators responsible for extracting information from the image operate at a lower level of resolution in the periphery. This position could be justified by arguing that high resolution for image inspection in the periphery is redundant since peripheral points of interest in the image can simply be moved to the center for closer examination.

In summary, therefore, under the constant grain size approach all linear radial transformations over unit distance should take equal amounts of time, whereas tangential transformations may be faster at the periphery than more central ones. In other words a plot of transformation time (y axis) against eccentricity (x axis) should be horizontal for radial transformations, and should show either a horizontal or monotonically increasing trend for tangential transformations. In contrast, under the varied grain size approach both curves would be sawtoothed, as discussed previously.

A Varied Resource - Constant Grain Size Approach

The two approaches above have both assumed equal allocation of image transforming resources (in terms of the frequency with which each cell is serviced) to all parts of the image. As mentioned, Kosslyn (1980 p. 140) did consider the possibility of differential allocation of resources but considered it unnecessary. Nevertheless, differential allocation of resources could account for some of the reported findings, such as the reduced acuity for peripheral parts of the image.

If image buffer cells in the central region were allocated more resources, or attention, then certain effects on the speed of image processing should follow. In particular, radial linear transformations should become faster closer to the center of the image, irrespective of direction, with a possible disjunction if there is a disjunction in resource allocation. One would also expect rotary or tangential transformations to be faster in the center, instead of the reverse trend predicted by the constant resources approaches.

To summarize this section, under the varied resource - constant grain size approach all transformations over unit distance (and most particularly radial transformations) should take less time in the center than in the periphery. In other words, a speed (y axis) X eccentricity (x axis) plot would show a positive slope throughout.

A Varied Resource - Varied Grain Size Approach

The possibility exists that resources are differentially allocated and the grain size is varied. For example, as the peripheral grain size increases (in the peripheral area) so resources allocated could decrease (such as, for example, if the cells were updated less frequently), to the point where such a system could behave in a way similar to the constant grain size, constant resource allocation approach, by showing a horizontal speed X eccentricity function for both radial and tangential transformations.

A differential resource and grain size structure combines the best aspects of both differential allocation approaches. The low resolution in the periphery gets a structural explanation and resources are efficiently allocated without incurring the distortions which would be expected to occur in transforming large objects in the other two systems.

The key to distinguishing between this approach and the constant grain size, constant resource model, which also predicts an essentially horizontal speed X eccentricity function, is the fact that under the varied grain size approaches a disjunction should occur as objects moving inwards become fully resolved and the need for an inverse mapping function ends, whereas no such disjunction would occur under the constant grain size model.

In summary, under the varied grain size, varied resource allocation approach all transformations over unit distance should take similar amounts of time (though a disjunction where the object becomes overprinted may exist). In other words, the speed (y axis) X eccentricity (x axis) function would be essentially horizontal, with a possible disjunction at some intermediate eccentricity.

Summary

Each of the four approaches above has its merits in terms of efficiency, parsimony or ability to account for aspects of the data. The approaches are distinguishable in terms of their predictions regarding the time required to perform transformations over fixed radial and tangential distances in the image. The specific distinguishing characteristics are:

1. A disjunction or change in the transformation speed function at some point between the center and the extreme periphery (characteristic of the varied grain models, and possibly true of a varied resource model).
2. The slope of the transformation speed function in the central and peripheral areas on each side of any disjunction (characteristic of the varied grain model).
3. The possibility of differences between radial versus tangential transformations (suggestive process differences).

The next chapter will specify hypotheses which cover these distinguishing characteristics and present experiments which were used to test them.

CHAPTER 3: THE EXPERIMENTS

A number of specific and testable hypotheses flow out of the discussion in the previous two chapters. Six hypotheses are presented in this chapter, and three experiments which were designed to test them are described. In addition, a re-analysis of the data from one of Jolicoeur and Kosslyn's (1985) studies is described. The hypotheses presented in this chapter have, for convenience, and where appropriate, all been expressed in such a way as to be consistent with a constant grain and constant resources approach.

Experiment 1

Individual differences are increasingly being shown to be important in imagery related tasks (see Cooper, 1976; 1982 for example). For this reason the imagery ability level of all subjects was tested and used as a blocking variable in subsequent analyses in the three experiments reported here. It was anticipated that low imagery ability scorers would be more inclined to rely on other non-image processes (e.g., tacit knowledge) in determining how rapidly to respond. Since these other methods are unlikely to be eccentricity dependant they are expected to reduce any eccentricity related effects in those subjects.

<u>Hypothesis 1</u>. Subjects who have low imagery ability scores will be less affected by the location of image transformations and will tend to produce more constant transformation speeds across different levels of eccentricity than will than those with high imagery ability scores.

The first image processing issue to be addressed will be the issue the time required to process central versus peripherally extended field general transformations, as well as the possibility of inward versus outward transformation time differences.

Hypothesis 2. Scanning between equally spaced elements in an imagined structure will take equal amounts of time, irrespective of whether the structure's elements

- remain all centrally located, or
- move radially in the periphery of the image.

A finding in agreement with the hypothesis would support the constant grain, constant resources and the varied grain, varied resources approaches. On the other hand, if the peripherally extended image were transformed more slowly the finding would support the constant grain, varied resources approach against the varied grain, constant resources approach, and vice versa if the extended image were transformed more quickly.

<u>Hypothesis 3</u>. Radial scanning between elements of an imagined structure that extends far into the periphery of the imagined visual field will take equal amounts of time irrespective of whether the body of the structure becomes <u>more</u> or <u>less</u> central during the scan.

This hypothesis addresses the question of the relative speed of inward versus outward movement of parts of an image. Under the constant grain size approaches, the direction of travel is irrelevant since no changes in resolution occur during scanning. Thus a finding of a difference between inward versus outward scanning times would be evidence against those approaches. Under the varied grain size approaches, however, inward travel is likely to be slower because of the need for memory access to resolve points moving into areas of smaller grain size. The inward/outward transformation time issue therefore provides a way of differentiating between the constant grain, constant resources and varied grain, varied resources approaches.

The object of Experiment 1 was to compare central versus peripheral linear radial image transformation speeds in which the whole image is imagined to move either into or out of the periphery (field general transformations). Note that the hypotheses refer to the effect of the eccentricity (central or peripheral) of all of the elements, while a subject scans between particular elements in the structure. This was accomplished by timing how long subjects took to scan between points in their images of simple stimulus figures. The points in the stimulus figures were arranged five degrees of visual angle apart and were spread out in such a way that relatively central and relatively eccentric scans could be compared.

Method

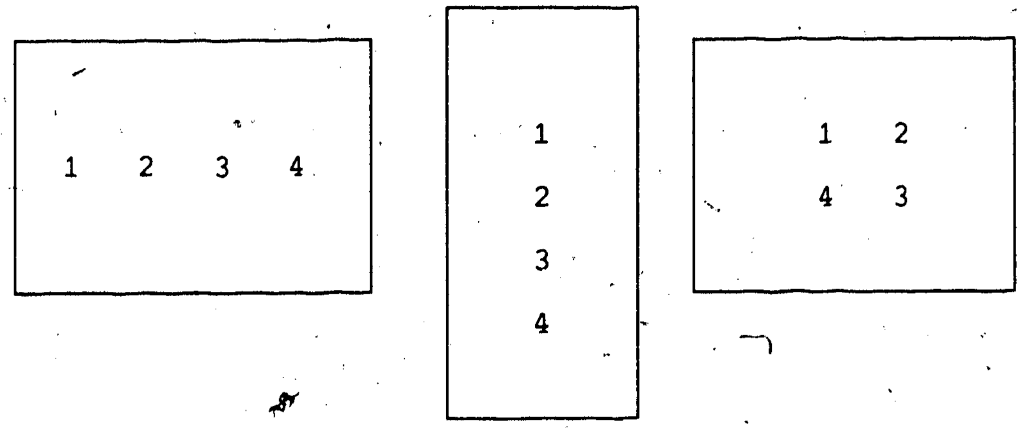
Subjects

Twenty three male volunteers from the University of Alberta community were paid $5.00 to participate. Of the 23 subjects tested, two did not finish in the hour allocated, one did not follow the instructions properly and two others were unable to get a visual, "picture-like" image of the test stimuli. The data from these five were omitted, leaving 18 subjects for further analysis.

Materials

Stimuli. The stimuli were made from white Lettraset letter "O"s (hereafter described as rings) approximately 3mm in diameter. The rings were arranged on black cards in various patterns and presented in a frame, level with the subject's eyes. The subject's chin was held on a chin rest which was adjusted so that the stimuli were at a distance of 340mm. The rings in all stimuli were arranged with adjacent rings 31 mm apart, or 5 degrees of visual angle.

Four different stimulus cards were used. The card used for the practice items had three rings arranged in a triangle. The three cards used in the actual test each had four rings arranged as illustrated in Figure 2. On the first test card they were arranged in a horizontal line, 31 mm apart. On the second test card they were vertically arranged, also 31 mm apart. Finally, on the third test card they were arranged in a square pattern, with each side of the square measuring 31 mm. These particular layouts were selected to allow comparison between performance on images which extend across a maximum of 15 degrees of visual angle (Patterns 1 and 2) versus an image which extends across only 7 degrees (Pattern 3). The horizontal and



Pattern 1. Pattern 2. Pattern 3.

Figure 2. Patterns for presentation of target objects in Experiment 1.

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vertical arrangement of Patterns 1 and 2 allow comparison with the horizontal and vertical sides of Pattern 3.

Imagery Questionnaire. Marks' (1977) Vividness of Visual Imagery Questionnaire (VVIQ) was used as a measure of imagery ability.

Response recording. The subject was provided with a panel with two buttons connected to an IBM PC. A computer program specified the item sequence to the experimenter (who called out instructions to the subject) and timed and recorded the responses.

Procedure

The full instructions used in all three experiments are provided in Appendix A. Only a precis is given here. The subjects were first given practice on a triangular stimulus. The subjects were asked to examine the stimulus card until they were able to form a "clear", stable mental image of the "rings" on the card with their eyes closed. The three rings were verbally labeled "1" to "3" clockwise around the triangle, with 1 being at the top.

Once they were able to form a clear image of the rings the stimulus card was covered with a blank masking card. Then, with their eyes closed, the subjects were asked to imagine themselves looking at a black dot as it moved "as quickly as possible" between a specified pair of rings. They were asked to first concentrate on the start position, and then when they were ready they had to press the left hand button on the response panel. Immediately upon pressing the button the subjects were asked to imagine that they could see the dot moving. It was stressed that they should not "lose sight" in their image of the moving dot, nor of any of the rings at any time. As soon as the moving dot had reached its target the subject had to press the right hand button to end the trial.

At any time between trials the subjects were permitted to open their eyes and look again at the stimulus card (the masking card was removed on request). In the practice items the subjects were asked to scan in a connected sequence to each of the three rings in a random route that was read out by the experimenter from the computer. For example, a given subject might have been asked "Scan from ring 1 to ring 3", "Scan from ring 3 to ring 1", "Scan from ring 1 to ring 2" in turn. This exercise (three scans, to each of the rings in a random sequence) was repeated six times, with each sequence, or route, constrained to be different from the previous one. Subjects were then offered the opportunity of repeating these practice items.

Once the subjects felt comfortable with the task and all their questions answered the three experimental stimulus cards illustrated in Figure 2 were introduced in a random sequence. The stimuli were presented in the same way as the triangular stimulus only each case the subjects were asked to scan the route 1, 4, 1, 3, 1, 4, 2, 4, 1. This route deliberately included rings 1 or 4 in every scan, so as to keep the maximum peripheral eccentricity of the figure constant for every practice item on a given figure.

Once these practice items had been completed the main study was begun. The test trials were presented in four blocks with a rest period between each block. In each block the three test stimuli, and their associated imagined movements, were presented in a random order (constrained to be different from the order in the previous block). Each test figure was shown to the subject in its turn, and the subject was asked to examine it until he could form a mental image of it as before. The stimulus card was then covered and the experimenter called out a connected scan route detailed in Table 1. This route has the following characteristics: it has two halves which were concatenated in a random order, the dot move-distance was never the same twice in a row, the dot move-direction alternated as much as possible, and every inter-ring interval was crossed equally often in each direction. For Patterns 1 and 2 there were six 5 degree scans, eight 10 degree scans, and four 15 degree scans. For Pattern 3 there were eight 7 degree diagonal scans, four 5 degree horizontal scans and two 5 degree vertical scans.

Table 1

Scan Sequence Used in Rings Experiment

	Part	
Move	A	B
1	1 - 4	4 - 1
2	4 - 1	1 - 4
3	1 - 3	4 - 2
4	3 - 4	2 - 1
5	4 - 2	1 - 3
6	2 - 3	3 - 2
7	3 - 1	2 - 4
8	1 - 2	4 - 3
9	2 - 4	3 - 1

Note. Parts A and B were concatenated in a random order.

When each subject had completed all the test items a blank sheet of paper was inserted into the stimulus frame and the subject was asked to draw the original stimulus figures exactly the same size as he remembered them. Finally the subject was given the VVIQ to complete at his own pace.

Results

The means and standard deviations of all the data are provided in Appendix B. All of the analyses reported below were performed with mixed design analyses of variance using BMDP. In each case the subjects were blocked according to VVIQ score (six subjects in each of three groups) and the subjects' recall of the actual size of the stimulus figures (the average inter-ring distance in all of their drawings) was used as a covariate.

The first analysis was of the time taken to scan across 5, 10, and 15 degree gaps in Patterns 1 and 2, by each of the three VVIQ groups. The design was 3 gap sizes X 2 pattern orientations X 3 VVIQ groups with the remembered figure size as the covariate. The results are provided in Table 2. As in most imagery-related studies, the effect of the absolute distance scanned was significant, $F(2, 34) = 21.69$, $p < .01$ (Greenhouse Geisser), but the effect of the covariate (remembered size), the VVIQ score, the figure orientation (Pattern

1 versus Pattern 2) and the interaction terms were not significant ($p > .05$).

Table 2

The Effect of Scan Distance and Pattern on Scanning Time.

	Scan Distance (Degrees of visual angle)		
Figure	5	10	15
Pattern 1	592	847	1027
Pattern 2	596	853	1014

Hypothesis 2 refers to the effect of the eccentricity of the whole figure during scanning. The effect was analyzed by comparing the time taken to scan across the center gap (rings 2-3, and 3-2) in the horizontal and vertical figures (where the most distant rings are at most 10 degrees from the fixation point) with the time taken to scan across the side gap (1-2, 2-1, 3-4, 4-3) in the two figures (where the most distant ring is 15 degrees away). The design was therefore Side-Center X Horizontal-Vertical X 3 VVIQ groups, with remembered Size as a covariate. The time required to scan across the eccentric gaps ($\underline{M}$ = 594 ms) was significantly less than the time to scan across the central gap ($\underline{M}$ = 606 ms, $\underline{F}(1, 15) = 4.69$, $\underline{p} < .05$). The covariate, VVIQ, Figure Orientation, and interaction effects were again not significant. The eccentricity finding was validated by comparing the time to scan the side gaps of the horizontal and vertical figures ($\underline{M}$ = 594 ms) with the time to scan the corresponding horizontal and vertical sides of the square figure, in which the most distant ring is at most 7 degrees from the fixation point, diagonally across the figure ($\underline{M}$ = [illegible] ms). The design for this analysis was therefore Figure (Extended figure versus Square figure) X Orientation (Vertical-Horizontal) X 3 VVIQ groups, with remembered average figure size as the covariate. The eccentricity effect was again significant ($\underline{F}(1, 14) = 13.29$, $\underline{p} < .01$), and no other effect was significant.

The effect of the direction of scanning, whether inwards or outwards, was tested in an analysis of variance of the time to scan only the outer gaps on the horizontal and vertical figures (since the inward/outward concept makes no sense in the case of all the other gaps). The design was Inwards-Outwards X Horizontal-Vertical figure X 3 VVIQ groups with the remembered Figure Size as the covariate. The effect of the inward/outward direction of scanning was not significant ($F(1, 15) = 2.08$, $p = .17$) but the values obtained are at least suggestive (see Table 3). The effect of the covariate, VVIQ and figure orientation was not significant.

Table 3

Inward versus Outward Scanning Times.

	Stimulus Figure		
Scan direction	Horizontal	Vertical	Mean
Inward	604	605	605
Outward	579	588	584

Discussion

The results obtained in this experiment show that the time required to scan across imagined gaps is influenced not only by the absolute distance scanned, but also in some ways by the rest of the figure which makes up the image, but is not part of the particular scan. Specifically, scan time is a function of the distance between the scan route and the rest of the figure, such that scans in which the most distant point is 15 degrees away from the scan route take less time to accomplish than scans in which the most distant point is only 10 degrees distant. These data are therefore consistent with the idea that the functional cell size in the periphery of the image substrate is larger than in the center, or that it requires less time or effort to update the location of peripheral parts of the image. Of course other interpretations are possible, the most obvious of which is that less attention is allocated to eccentric parts of the image, thereby freeing capacity for processing the remaining parts. Clearly more data are needed. In particular a range of levels of eccentricity on different kinds of tasks would be more informative.

Experiment 2

In Experiment 1 the subjects were asked to track an imagined "black dot" as it moved across the image.

Since they were to imagine themselves looking at the dot as it moved (holding it in a mental fovea, so to speak), the location of the bulk of the pattern in the image changes with respect to the fixation point during each trial. This is what Kosslyn referred to as a field general transformation. The findings in Experiment 1 do not necessarily generalize to local or region-bounded transformations in which only a small part of the image moves with respect to the fixation point. Furthermore, if the findings of Experiment 1 do not generalize to local transformations, then the interpretation of those results will be drastically affected. Experiment 2 was therefore intended to test for eccentricity effects in local, or region bounded transformations, and to provide a range of degrees of eccentricity for closer examination of the eccentricity effect. It should be noted, therefore, that in this experiment the object of interest is the eccentricity of a part of the image, not the whole image as is the case in Experiment 1.

The experiment was designed to test two hypotheses which are provided below.

<u>Hypothesis 4</u>. If an object is imagined to move radially at constant speed across equal intervals which are at different distances from the center of the image, the time taken to traverse the interval will be equal for all levels of eccentricity.

<u>Hypothesis 5</u>. If an object is imagined to move radially at constant speed across equal intervals which are at different distances from the center of the image, the time taken to traverse the distance will be equal for inward moving and outward moving steps.

Results in agreement with Hypotheses 4 and 5 would support the constant grain, constant resources and varied grain, varied resources approaches, whereas under the constant grain, varied resources approach the peripheral transformations should be slower, and under the varied grain, constant resources approach one would expect peripheral transformations to be faster.

These hypotheses were tested by having subjects imagine a "ball" to move back and forth between imaginary points arranged two degrees of visual angle apart, and positioned between two and thirteen degrees from the fixation point.

Method

Subjects

Twenty four male volunteers from the University of Alberta community were paid $5.00 to participate. The subjects were all undergraduate psychology students. Of the 24 subjects tested, three said they were unable to imagine the scene required, a fourth imagined the scene from a perspective other than the one instructed, a fifth had difficulty imagining the scene and did not complete the task in the allotted time, and equipment problems prevented a sixth from finishing in the allotted time. These six were omitted from the study, leaving 18 subjects for further analysis.

Materials

Stimuli. The stimuli were made from black lines and straight pins with colored heads arranged on a 360 mm X 180 mm board as illustrated in Figure 3. A yellow colored pin at one end of the board represented the subject. Radiating out from the subject pin were a set of radii extending to an arc 340 mm from the subject pin. The radii extended to each of four pins which were positioned 2 degrees of visual angle apart (from the perspective of the subject pin). These four pins were described as "player" pins. The radii also extended to another four pins on the arc. These red colored "fixation" pins were positioned 2 and 8 degrees to the left and to the right of the player pins. The result was such that, from the perspective of the subject pin, eight other pins could be seen at the end of 340 mm radii. These pins were so arranged that all inter-player angles were 2 degrees, and that each inter-player span was 3, 5, or 7 degrees to the left or right of the inner fixation pins, and 9, 11, or 13 degrees from the outer fixation pins.

Imagery questionnaire. Marks' (1977) Vividness of Visual Imagery Questionnaire (VVIQ) was used as a measure of imagery ability.

Response recording. The subject was provided with a panel with two buttons connected to an IBM PC. A computer program specified the item sequence to the experimenter who called out instructions to the subject and the computer timed and recorded the responses.

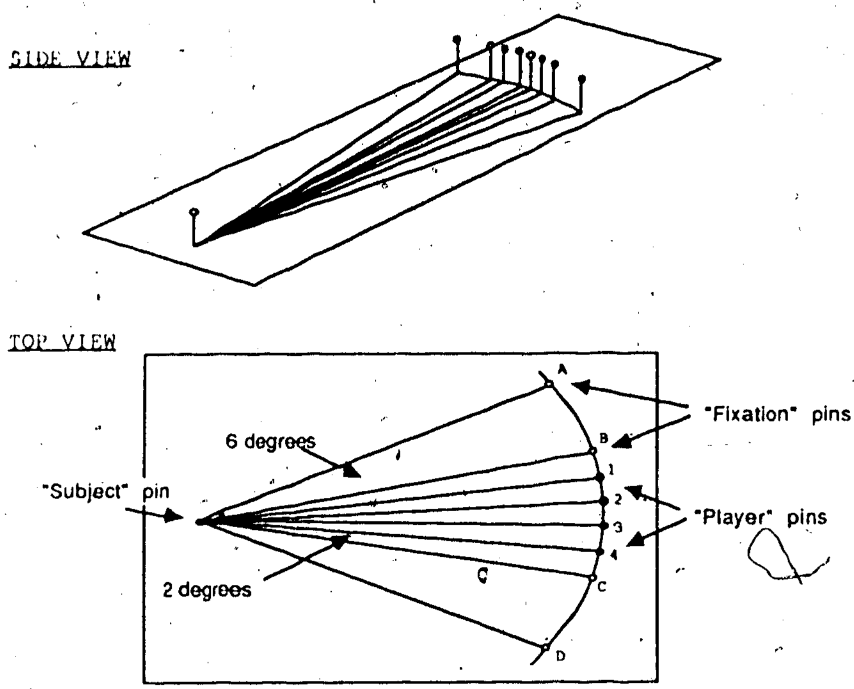

Figure 3. Experiment 2 stimulus array. Note that on the actual apparatus no letters and numbers appeared.

Procedure

The full text of the instructions is provided in Appendix A. When the subject was seated he was shown an image on the computer screen of two upright pin shapes approximately 20 mm apart. After a click sound from the computer a ball shape (four adjacent pixels in a square) moved at a constant speed in a parabola between two pin figures. The ball took approximately 2 seconds to make the transit. After a few seconds another click sounded and the ball travelled back to the first figure. This was repeated five times in all. The subject was told while he was watching that this was an image of two figures playing a ball game.

Next the subject was shown the board apparatus illustrated in Figure 3 and the instructions were given. The subjects were shown the apparatus and asked to hold it in such a way that they could see what the subject pin could see (i.e. with the subject pin near to one eye). The four player pins were given the names Player 1 through 4 and the subjects were told that they would be asked to imagine a ball game going on, with the ball being thrown in an experimenter specified sequence, between the player pins. The fact that the all of the pins were equidistant from one another and equidistant from the subject pin was pointed out. Once the subjects understood this, they were told that their task would be to imagine the ball movements while fixating the red fixation pins which were given the labels A through D. For example they were asked, "Fixate Pin A. Imagine the ball to be thrown from player 1 to 4, (Subject operates the timer) Player 4 to 1," and so on.

The subjects were then instructed that when they were ready to imagine a given ball throw, on a route specified by the experimenter (for example from Player 1 to Player 3), they should press one button. Immediately upon pressing the button they were to imagine the ball to be thrown. As soon as the ball was imagined to arrive at its target they should press the other button.

The subjects were asked to choose which of the two buttons they thought was the start, and which the stop button. All chose the left button to be the start button, and the right button to be the stop button.

During the instructions the subjects were allowed to examine the apparatus from any angle, but were told to imagine the scene from the perspective of the subject pin. They were given as much time as they wanted to examine the apparatus and attempt to form the image. Most were able to understand the instructions and reported that they could imagine the scene within a few minutes. Three, however, could not. Those who could not imagine the scene filled out the VVIQ and were released.

Once the subject reported that he was ready he was asked to close his eyes and imagine the scene. The subject was then asked to fixate pin A, B, C, or D in a random sequence while imagining a ball being thrown from player 1 to 4, 4 to 1 and so on over a connected route, pressing the buttons as appropriate. The complete ~~route is~~ described in Table 4.

Table 4

Scan Sequence Used for Practice in Experiment 2.

Move	Route
1	1 - 4
2	4 - 1
3	1 - 3
4	3 - 1
5	1 - 4
6	4 - 2
7	2 - 4
8	4 - 1

The practice route was selected such that the ball always travelled 4 or 6 degrees (note that only the 2 degree move times in the test trials were analyzed). The subjects were allowed to repeat the practice items as often as necessary until they were comfortable with the task.

The test items were presented in 4 blocks, with a rest between each. In each block there were four sets of items, one for each of the four fixation pins which were selected in a random sequence. In each set the subject was asked to fixate a particular fixation pin in his image, and, while fixating the pin, to imagine the ball to be thrown along the same 18 step route used in Experiment 1, detailed in Table 1. At any time between sets the subject was permitted to examine the model again.

Once he completed the test trials the subject's head was placed in a frame and a blank sheet of paper was positioned 340 mm in front of him. He was then asked to draw the relative locations of the player and fixation pins as they would be seen from the perspective of the subject pin.

Finally the subjects completed the VVIQ, were paid, thanked, and released.

Results

The means and standard deviations of all of the data are provided in Appendix B. The ball movement time for two degree movements was subjected to a mixed design analysis of variance, and the significance of the polynomial effects was calculated. The design was eccentricity (3, 5, ... 13 degrees away from the fixation point, without regard for direction) X direction of movement (in-out from the fixation point) X 3 VVIQ groups. The results are illustrated in Figure 4 and in Figure 5. The main effects of eccentricity, movement direction and VVIQ group were not significant, nor were any of the interaction terms.

Since some of the models described in Chapter 2 specifically predict a disjunction in the movement times X eccentricity function, and changes in the shape of the function at different levels of eccentricity, the data were tested for orthogonal polynomials. The quadratic component of the eccentricity factor was significant ($F(1, 15) = 10.29$, $p < .01$) as was the interaction between the inwards/outwards factor and the quadratic component of eccentricity ($F(1, 15) = 8.31$, $p < .05$).

The interaction between the inward/outward factor and Eccentricity is apparent in Figure 5. The inward moving times show less quadratic effect than the outward moving times. The effect is nonetheless reliable in both curves as evidenced by the fact that the 5 degree time for inward moving images is significantly longer than the 3 degree time ($F(2, 58) = 2.38$, $p < .05$) and the 9 degree time ($F(2, 58) = 2.27$, $p < .05$) (both calculated by means of Scheffe's

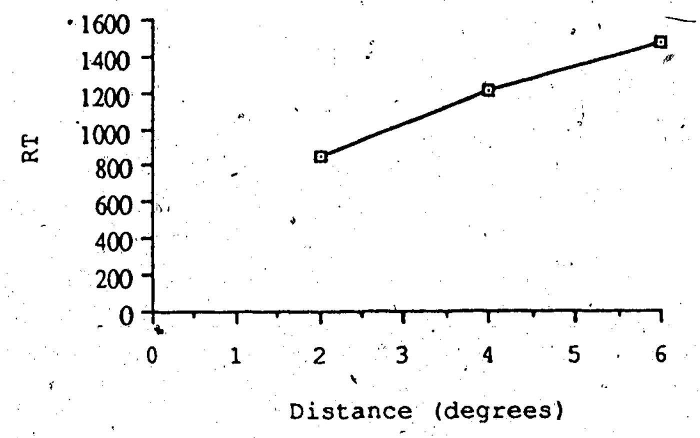

Figure 4. Movement distance effect.

F). The same is true for the outward moving images, with the 3 degree times being significantly faster than all other angles together ($F(2, 58) = 2.2218$, $p < .05$)

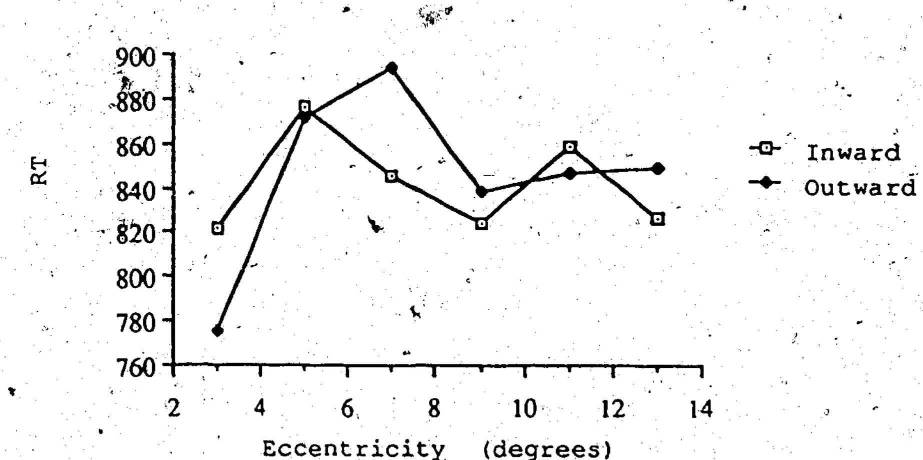

Figure 5. Inward versus outward movement time.

and the 7 degree time significantly slower than the 9 degree time ($F(2, 58) = 2.448$, $p < .05$). The interaction between the inward/outward and eccentricity factors is Therefore primarily due to the fact that the 3 degree and 7 degree times for inward versus outward moving images are different, with the inward time at 3 degrees non-significantly slower ($F(2, 58) = 2.719$, $p < .10$), and non-significantly faster at 7 degrees ($F(2, 58) = 2.93$, $p < .10$).

Discussion

The central finding in this experiment is a quadratic effect in that the time taken to imagine movements is greater for movements at intermediate eccentricities around five to seven degrees, than for central and peripheral movements. This effect is reliable in both inward and outward movements, despite an interaction which suggests that the curve might be flatter for inward movements. The hypothesis of equality of movement time can therefore clearly be rejected, though the meaning of the results is not clear. A full discussion and interpretation will be held off until the next chapter.

Experiment 3

The previous two experiments involved image transformations in which the image, or parts of it, moved directly towards, or away from the center of the image buffer. To clinch the issues raised in the first two chapters, however, it is necessary to show that the eccentricity effects seen in Experiments 1 and 2 are also true in the case of non-radial transformations, or imagined movements which are at right ~~angles to~~ hypothetical radii extending out from the imaginary fixation point. Experiment 3 therefore provides a test of Hypothesis 6 which is provided below.

> <u>Hypothesis 6</u>. If an object is imagined to fall from a constant height at various horizontal locations, the time taken for the falling object to be imagined to reach the ground will be constant, irrespective of the horizontal eccentricity of the imagined event.

The question being addressed in Hypothesis 6 is the speed of tangential transformations as opposed to the radial transformations of the previous hypotheses. Under the constant grain, constant resources and varied grain, varied resources approaches the hypothesized outcome should occur. On the other hand, under the varied grain, constant resources approach one would expect the peripheral transformations to be faster, and under the constant grain, varied resources approach they would be expected to be slower. As discussed previously, however, tangential transformations such as these might be overlayed by an operator which serves to reduce the torsion resulting from rotary transformations by slowing central rotary transformations. As a result an outcome which shows the peripheral transformations to be equally fast or faster will have to be interpreted with caution. On the other hand, if the peripheral transformation is found to be slower, it will constitute particularly strong evidence for the varied resource approaches, and against the constant grain, constant resources approach.

In the experiment designed to test this hypothesis subjects were asked to fixate a point on a screen before them, while imagining objects to move vertically downwards through visual angles of two, three or five degrees. The movement distance and eccentricity was manipulated by providing movement start and end points on the screen, and the time taken to imagine the movement was recorded as before.

Method

Subjects

Twenty eight male volunteer undergraduates from the psychology department were paid $5.00 to participate. Of the 28 subjects run, five were unable to finish in the hour allocated due to the length of the task, three were unable to create or maintain the image required and two did not, or were not able to follow the instructions properly. These ten were omitted, leaving 18 subjects for further analysis.

Materials

A frame was used to hold the subject's head 340mm from a black and white RCA monitor. The experiment was controlled by a program running on an IBM PC.

Stimuli. The stimuli were images like that in Figure 6 presented 340 mm in front of the subject's eyes on the monitor. The gain on the monitor was adjusted such that the two horizontal lines were vertically separated by a 2-, 3-, or 5-degrees gap, and the lines were approximately 32 degrees of visual angle from end to end. A small fixation point was located at the exact middle of the figure and did not move throughout the study.

As illustrated in Figure 6, from the top horizontal line a line extended upward for two degrees of visual angle, and directly below it a similar line extended downward from the bottom horizontal line. These vertical lines were positioned either immediately above and below the fixation point (only during the instructions) or multiples of 2 degrees up to 14 degrees to the left or to the right of the fixation point.

<u>Imagery Questionnaire</u>. Marks' (1977) Vividness of Visual Imagery Questionnaire (VVIQ) was used as a measure of imagery ability.

<u>Response recording</u>. The subject was provided with a panel with two buttons connected to the computer which recorded all button presses and time lapses.

Procedure

The full text of the instructions is provided in Appendix A. Only a precis is given here.

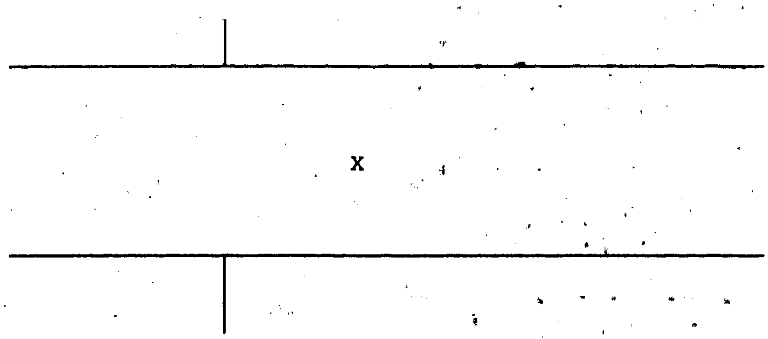

Figure 6. Experiment 3 stimulus

At the beginning of the session the chin rest was fitted to the subject and the screen set the correct distance away. Then, while the subject's head was still correctly positioned, 8 demonstration examples were displayed on the screen. In the demonstration examples the horizontal lines were shown on the screen 3 degrees apart, and the vertical lines were positioned immediately above and below the fixation point. After a 1 second pause a tone sounded and a dot appeared to move down from the top vertical line, through the fixation point, to the lower vertical line, taking about one second for the transit. The subject was asked to fixate the point in the middle of the screen while watching the moving point which was described as a falling ball.

At the conclusion of the demonstration examples the subject was told that he would be asked to look at the fixation point on the screen (eyes open) while imagining "a steel ball, or a raindrop" falling between the two horizontal lines, from the top vertical line to the bottom one. The subject was instructed to signal his readiness by pressing the left response button. Immediately upon pressing the button the subject had to imagine the ball to be released from the upper vertical line. When the ball was imagined to reach the bottom line he was to press the right hand button.

Next the subject was given 17 practice items using the buttons as discussed above. In the practice items all 14 horizontal drop eccentricities, and all three drop distances were presented.

The test items were made up as follows. The 3 vertical distances and the 14 different horizontal locations provide for 42 unique items. For the test trials the full set of 42 test items was blocked, and the block was presented in individually randomized order, 5 times over. The items were presented in half blocks of 21, preceded each time by two dummy items (12 degrees left and right of fixation, three degree drop).

After each half block the subject was permitted to rest his eyes as long as he wanted.

Finally, once the subject had completed all of the items he filled out the VVIQ at his own pace.

Results

The means and standard deviations of all the data are provided in Appendix B. The data were subjected to a mixed design analysis of variance, and the significance of the polynomial components of the eccentricity effects was calculated. The design was eccentricity (1, 3, ..., 13 degrees from the fixation point, irrespective of direction) X drop distance (2, 3, 5 degrees) X 3 VVIQ groups. The results are presented in Figure 7 and Figure 8.

The main effects of VVIQ group and Eccentricity were not significant at the $p=.05$ level. The drop distance factor was significant ($F(2, 30) = 55.44$, $p < .01$ (Greenhouse-Geisser)) with longer drop distances taking longer to imagine. The Drop time also interacted with the VVIQ group factor ($F(4, 30) = 3.78$, $p = .041$ (Greenhouse-Geisser)) but the drop distance effect is in the same direction for all three VVIQ groups and the simple main effect is also significant

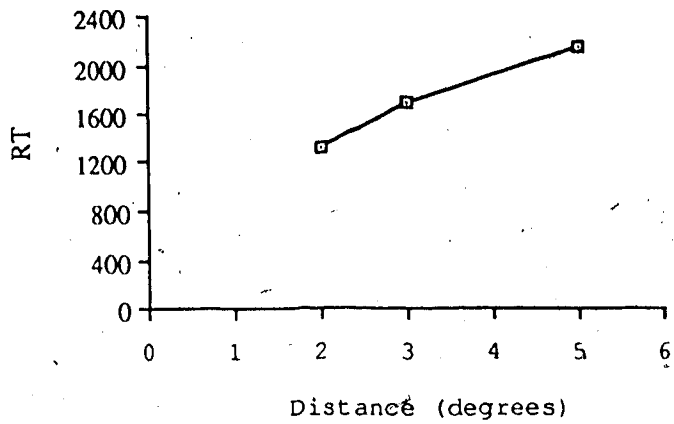

Figure 7. Drop distance effects

in all cases ($F(2, 30) = 42.307, 8.0226, 12.6826$ for the low, medium and high VVIQ groups respectively, $p < .01$). The simple main effect of the VVIQ group factor, on the other hand, does not reach the $p = .05$

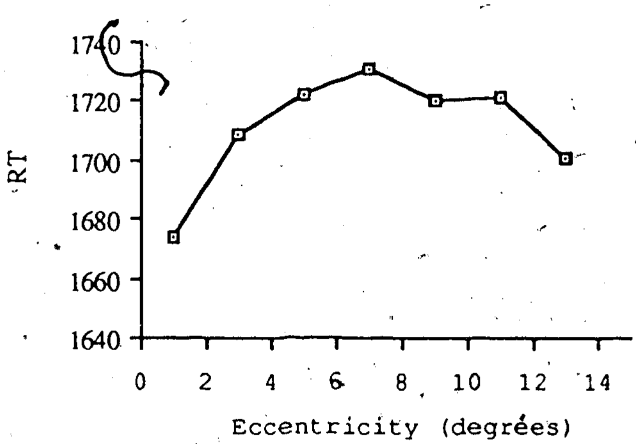

Figure 8. Drop time eccentricity effects

level for any drop distance. The interaction term thus reflects only a difference in the degree of the distance effect for the three groups.

As might be inferred from Figure 8 there is a significant quadratic component to the eccentricity factor ($\underline{F}(1, 15) = 5.12$, $\underline{p} = .039$).

Discussion

The data in Experiment 3 show the usual distance effects found in most mental travel experiments, plus a non-linear eccentricity effect. The data are particularly convincing in this experiment since the span that the imagined object was to cross was <u>visually</u> presented during the task, thereby eliminating the possibility that it was the distance of the imagined move that was distorted and caused the effect.

The task in this experiment is extremely simple, since the subject has only to imagine the falling object. All other parts of the scene are provided on the screen. From a processing point of view, the imager has only to imagine the movement of a single object in a straight line, the location of which is specified visually. The subject does not have to manipulate or even refresh other parts of the image.

This is in striking contrast to the previous experiments in which the subjects had to hold everything in memory and were specifically instructed to not "lose sight" of the other parts. Despite this difference in the processing and attention requirements, the results are essentially the same in all of the experiments. In addition the slowest point, around 7 degrees, is the same in all three experiments.

External Validation

Eccentricity effects were found in all three of the experiments performed in this investigation. As a kind of external validation of the results, I sought another, independent investigation amenable to an analysis of the eccentricity effects. No other experiments that I found seemed to be very suitable for a comparative analysis, but the standard map scanning method first used by Kosslyn, Ball & Reiser (1978) does provide eccentricity data, though it is somewhat confounded with the absolute distance effect. Accordingly, the data from Experiment 3 of Jolicoeur and Kosslyn (1985)[1] were re-analyzed in terms of the effect on scanning time of the relative eccentricity of different parts of the image.

Method

In their experiment, Jolicoeur and Kosslyn (1985) had 4 groups of 12 subjects, each with its own experimenter, study a hypothetical map of an island with seven locations marked on it. They studied the map until they felt they had an accurate image of the map and were able to reproduce the locations of the seven locations with reasonable accuracy. The subjects were then asked to imagine the map and focus on particular locations "while keeping the entire map in view in the mental image" (Jolicoeur and Kosslyn, 1985, p. 322) and then track an imaginary black dot as it moved as fast as possible to other named targets. The subject pressed a button to indicate when the dot arrived at the target on each trial.

The four experimenters in Jolicoeur and Kosslyn's study were given different expectations about the

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[1] The data were kindly supplied by Pierre Jolicoeur

outcome of the experiment -- without effect. Nevertheless, the four experimental groups have been kept distinct in this analysis. In another part of their study the subjects scanned visible maps, as opposed to imaginary ones, but those data have no bearing on the present study.

For the present analysis, a measure of the eccentricity of all locations from a given scan route was calculated, and its effects on the scanning time assessed. The eccentricity measure for each inter-point scan was taken as the average distance between the both the start and the finish points and all other named points on the map. For example the Lake-Tree gap is the shortest distance that people were asked to mentally scan on the map in Jolicoeur and Kosslyn's study. The eccentricity metric for this route was calculated by averaging the distances between the lake and each of the 5 other named points on the map (other than the tree), as well as the average distances between the tree and the other 5 points. To be sure, this metric ignores the eccentricity of un-named parts of the map (the coastline, etc) and ignores the fact that the eccentricity of the named locations from a given route changes as one scans along the route, and that change is a function not only of the average-distance at the start and end points, but also of the orientation of the route with respect to the location. Nevertheless, these limits and sources of additional noise should serve to bolster the credibility of any significant results obtained.

It was mentioned above that the eccentricity effect is to some extent confounded with the distance effect. That is, because of the way in which Jolicoeur and Kosslyn arranged their map (with short spans in the center, and longer spans crossing the center), there is a correlation of r = .84 (or 70% overlap) between their distance measure and the route eccentricity measure. For this reason the linear effect of distance was arithmetically removed from the data prior to the analysis. It would not have been possible otherwise to guarantee the orthogonality and purity of the polynomial contrasts. That is, the best fitting line for time against route distance was calculated in Jolicoeur and Kosslyn's data, and the predicted times were subtracted from their data. Having removed the distance effect from the data there is no question of interaction between the contrasts and linear distance-related effects. There are of course certain consequences of this adjustment which I will return to in the discussion.

Results

The means and standard deviations of all the data are given in Appendix B. Figure 9 illustrates the relationship between the residual RT and the eccentricity of the other objects in the map. The figure displays the characteristic shape found in Experiment 2 and 3 of this study (note, however, that the units on the X axis in Figure 9 are not degrees as they were in the previous eccentricity figures).

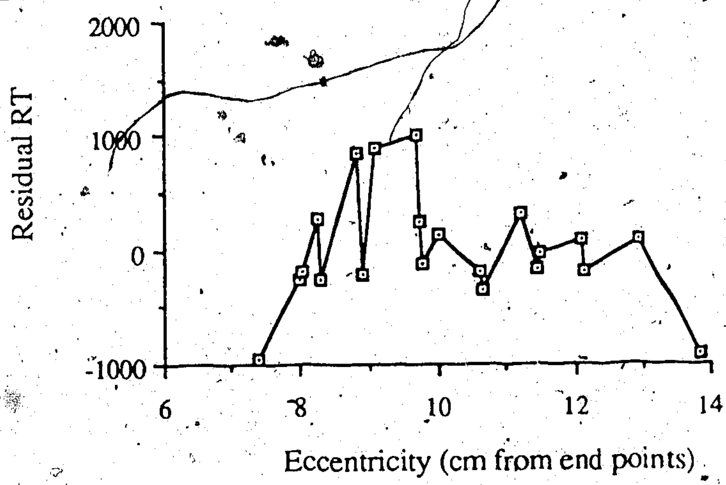

Figure 9. Eccentricity effects in Jolicoeur and Kosslyn's data (after the removal of the linear distance effects).

The data were analyzed by means of a mixed design analysis of variance using BMDP. The design was route eccentricity (21 levels) X 4 experimental groups, with the residual RT as the dependent variable. As in Experiments 2 and 3, orthogonal polynomial contrasts were performed on the eccentricity effect (corrected for the non-monotonicity of the eccentricity variable). One might argue that the prior removal of the linear effect of distance reduces the degrees of freedom of the dependant variable, and so one degree of freedom in the denominator was be given up. This adjustment makes no difference to the results in this case, however.

The experimental groups effect was not significant ($F(3, 44) = .72$, $p > .5$) but there was a significant effect of eccentricity ($F(20, 879) = 3.99$, $p < .01$ (Greenhouse-Geisser corrected)). While the linear effect of eccentricity is not significant ($F(1, 44) = .25$, $p > .5$) (but see below) the quadratic, cubic and quartic effects are all significant ($F(1, 44) = 15.16$, 9.14 and 14.09 respectively, $p < .01$).

Discussion

The results from this re-analysis of Jolicoeur and Kosslyn's data show the same trends as found in ~~my own~~ studies. That is, transformations in which the bulk of the image is relatively central, or relatively eccentric are quicker than those in which the image is at an intermediate distance.

The confounding of eccentricity and distance in the present analysis has two consequences. First, it means that in removing the linear effect of distance from the data, I have also removed the linear portion of the effect of eccentricity -- hence the lack [illegible] linear effect in the data. More generally though [illegible] confounding means that if this [illegible]nt were viewed in isolation rather than in the [illegible]f my experiments just reported, the effects found [illegible] eccentricity could all [illegible]ttributed to polynomial <u>distance</u> effects. In fact, orthogonal polynomials based on the distance of each route explain almost as much of the variance (12.25%) as do the polynomials on eccentricity (13.93%) in the first 10 polynomial components (calculated according to the method provided in Myers, 1979, p. 85).

The questions of distance-as-cause versus eccentricity-as-cause are inseparable in this context and so it boils down to a matter of plausibility of one model over the other. On the face of it the two are equally plausible, but there are two factors which weigh the balance somewhat. First there is the prior prediction of the eccentricity effect as against the fact that current theory of mental scanning makes no provision for polynomial distance effects. Second is the point the eccentricity metric accounts for marginally more of the variance of the data.

In conclusion, Jolicoeur and Kosslyn's study serves as an external validation of the eccentricity effects found in my own three experiments.

CHAPTER 4: DISCUSSION

In the first few paragraphs of this discussion I will review the results of the experiments in the light of the formal hypotheses set out in Chapter 3. Thereafter I will discuss the more general implications of the results, referring in particular to the different possibilities for the image substrate raised in Chapter 2. Finally, I will speculate on the broader theoretical implications of the results, and discuss some of the research questions which flow from this work.

Hypothesis 1 was concerned with the relationship between imagery ability of the subjects and their image transformation times. The subjects' VVIQ scores were used as a blocking variable in every analysis, but in no case was a significant effect of VVIQ score found. Of course this does not mean to say that a VVIQ effect would not be found in experiments specifically designed to detect such an effect, as opposed to the present study where the test was made merely to reduce a possible source of error variance.

Hypotheses 2, 4, and 6 in Chapter 3 all refer to the effect of eccentricity on transformation time in mental images. In Experiment 1, field-general scanning time was significantly longer for those inter-point spans in which remote parts of the image were between 5 and 10 degrees away than for those scans in which the most distant parts were 10 to 15 degrees away. In Experiments 2 and 3 transformations at moderate levels of eccentricity around 7 degrees also took longer than more eccentric and less eccentric transformations did. Finally, in the re-analysis of Jolicoeur and Kosslyn's (1985) scan time data significant polynomial effects of eccentricity were found. Formally speaking, therefore, the three hypotheses can be rejected because an eccentricity effect was found in all four of the experiments.

Hypotheses 3 and 5 refer to the relative speed of inward versus outward transformations. In Experiment 1 there was no significant difference. In Experiment 2 there was a significant interaction between the direction of movement and the quadratic component of eccentricity such that at around 7 degrees of eccentricity inward transformations were faster than outward, whereas more centrally the reverse was true. Overall, therefore, the results on the question of the effect of direction of movement are suggestive, but inconclusive.

To summarize, the experiments have all shown a non-linear, eccentricity-related image processing effect. In Chapter 2, four combinations of Varied versus Constant Grain size, and Varied versus Constant Resource Allocation were discussed. It was noted there that constant grain size would result in a horizontal Transformation Time X Eccentricity curve, and that the allocation of extra processing resources to the central area of a constant grain image substrate would speed central processing at the expense of peripheral processing, resulting in a curve which is upward sloping. The experiments reported here clearly do not support the constant grain position (irrespective of resource allocation), as the more eccentric parts of the curve are downward sloping in all four experiments.

In discussing the likely effects of varied grain size and constant resource allocation in Chapter 2 it was noted that the simplest method of moving parts of an image, the total transfer option, would result in a linear downward sloping transformation time X eccentricity function. The data clearly do not support this approach either, as quadratic effects were found in Experiments 2 and 3 as well as in Jolicoeur and Kosslyn's (1985) data. Of all the combinations of grain size and resource allocation considered, the data are consistent only with the models which postulate varied grain size and constant resource allocation (the check for overprinting option and the check precise position option).

Of course, the fact that the data are consistent with the constant resource, varied grain size model in no way proves the validity of the model. I will try, nevertheless, to establish the plausibility of the model by exploring what one <u>can</u> conclude from the data.

Under a propositional approach (e.g. Anderson, 1983), the present results would be explained by reference to some aspect of the processing of the data, or some other confounding issue such as the tacit knowledge of the subject. I will examine the processing explanation first, and then look at the question of tacit knowledge.

Under the propositional approaches the spatial location, speed of movement, and distances of imagined objects are all symbolically represented. As such, the distance of an object from an imagined fixation point makes no difference to the processing of that point. That is, the addition or subtraction of 10 units of distance to a variable representing the eccentricity of an object (e.g., in imagining movement of an eccentric object) should not be affected by the starting value of the distance variable, yet this is what seems to happen in the case of Experiments 1 and 2. Furthermore, in the case of Experiment 3, the eccentricity variable hardly changes at all (since the eccentricity of the falling objects remains more or less constant, particularly for the more eccentric objects). Only the relative height of the imagined objects changes, and yet the magnitude of the distance appears to affect the processing speed. There seems to be no explanation which can be based upon purely symbolic representations of the parameters involved.

The most common criticism leveled at the mental travel studies is that the subjects' tacit knowledge of physics, or of the goals of the experiment, make them produce the distance-related reaction times so commonly found. In the case of the experiments reported here there are no physical reasons (outside of the central nervous system) for differences in transformation time as a function of the eccentricity of parts of an object (viz. Experiment 1 and Jolicoeur and Kosslyn, 1985) or of the moving object itself (viz. Experiments 2 and 3). Furthermore, to predict the effect obtained requires a thorough understanding of Kosslyn's theory, and its more subtle implications. It seems unlikely that my subjects, all of whom were undergraduates, would have been able to bias their responses so consistently. There seems little doubt that the effect is real. The only question is what causes it.

A variant of the varied resource allocation model is as follows. It could be that in processing images the brain may economize on processing effort by giving less attention to objects imagined to be more than a certain distance from the imagined fixation point (irrespective of whether distance is represented in a propositional or analogue manner). Alternately, resources may be diluted by being spread over a wide area, irrespective of the number of objects in that area (an idea which only makes sense in an analogue model). Since the subjects were instructed (in Experiments 1 and 2) not to lose sight of the other objects, they were in effect told to give attention to all parts of the image. This distribution of attention over a wide area could slow the processor, leading to the initial increase in processing time found in the studies reported here. Then, for objects imagined to be still further from the fixation point, the brain might "give up" and ignore the object, freeing resources, which would speed processing. The latter would then lead to the decreases in processing time found for more eccentric items.

This argument may be plausible in the case of Experiment 1 and Jolicoeur and Kosslyn's work because in those studies there were a number of eccentric objects which the subject could safely ignore. In the case of Experiments 2 and 3, however, there is only one part of the image where any activity occurs, and where attention (as opposed to gaze) is required. Posner (1980), Posner, Nissen and Ogden (1976), and Remington (1980) have shown clearly that attention can be easily shifted away from the point of focus in vision, and Pinker (1980) has shown it in imagery. There seems no reason why the subjects would not have been able to do so in this case. Furthermore, if they did "give up" and stop attending to the one and only moving part of the image in the more eccentric items, it seems unlikely that their response times would produce such a consistent and reliable curve. Attention differences, therefore, seem an unlikely explanation of the present findings.

The analogue model explains the data parsimoniously. Notwithstanding Anderson's (1978) point that a propositional algorithm could be written to provide any desired outcome, the prior prediction of irregularities in the transformation time/eccentricity function on the basis of an elaboration of an analogue model outweighs the fact that the propositional approach can be modified to accommodate the finding (Hayes-Roth, 1977). On the basis of the data available I would argue that, at the very least, the brain does employ a functionally spatial medium in mental image processing. For convenience I will continue to call it an image buffer after Kosslyn (1980). The image buffer does not necessarily depict the image, and does not necessarily contain all the information necessary to fully describe the experience of the imager, but it <u>is</u> used at least as a scratch-pad in the course of image processing, and contains at least skeletal place-holder information representing the spatial location of imagined objects. For example, a given part of an object or scene, such as a particular motorcar in an imagined street scene, would be represented in the image buffer by perhaps as little as one or two markers, linked in some way to a more complete representation in memory of the object being represented. These markers could be moved about in the image, in areas of high or low resolution, without necessarily being more completely resolved, but their close association with the deeper representation of the object itself would provide the capability to zoom in, as one seems to be able to do mental images, or to fill in some of the missing data without zooming.

The processor probably uses each marker as a reminder about the existence of an object or part of the object in that location, and then uses separately stored information about the object's movement direction, velocity, axis of rotation and so on to calculate the new location of that point after the cycle. Since each point is treated individually, significant distortions as a result of the substrate grain size or differential speeds of parts of rotating objects do not occur.

In those cases where the marker is not fully resolved, and it is being transferred to a new location, then an inverse mapping process is needed to determine whether the resolution of the marker should change during the move, or not. This extra process of course takes time, increasing the total time required to update the image. Note, however that this inverse mapping exercise is necessary only in the region that is not fully resolved, and only when the cell is being altered. As an object is imagined to move inwards it moves over smaller and smaller cells and therefore needs to be moved to a new cell more and more frequently per degree of visual angle. The inverse mapping process is therefore used more and more frequently. This increases the load on the processor, giving rise to the increase in processing time between 13 and 7 degrees of eccentricity that was found in the experiments.

Once an object is fully resolved at the chosen level of resolution it probably moves to a new cell on every cycle, but the inverse mapping function is not needed since no further increases in resolution are wanted (note the discussion in Chapter 1 of the fully resolved area of the buffer under Kosslyn's model). This reduces the processing effort, leading to the reduced processing time seen for more central transformations in Experiments 2 and 3 and in Jolicoeur and Kosslyn's (1985) data.

Until now the implications of the results from imagery research have had little impact on fields other than the general field of spatial cognition. This is no doubt largely because of the fact that the close parallels between imagery and the physical world have meant the effects of the use of imagery could not easily be separated from the effects of physical laws and tacit knowledge of those laws. These new findings suggest a means of making that distinction, since now we know ways in which images do not behave in exactly the same way, as the physical world, and so we can now look for that those effects in other aspects of human behavior. For example such illusions as the Tunnel illusion in which a point moving towards and through an opaque tunnel appears to have slowed down in the tunnel, or to take too long to emerge (see for example Wenderoth and Johnson, 1983) can be explained by reference to this model of the image buffer.

In the case of the Tunnel illusion the subject first views a point moving at a regular rate towards the tunnel. The tunnel at that stage is relatively eccentric, (or the point is, if the subject fixates the tunnel) and so the subject learns the speed of movement of the point while parts of the display are quite far from the fixation point. When the dot moves into the tunnel and subject has to imagine the movement to continue, the tunnel and invisible point are centered in the image, and therefore less eccentric. Under those circumstances the present research has shown that the image is more quickly processed and so one would expect the imagined dot to arrive at the exit of the tunnel ahead of time, which is precisely what happens. The test of the applicability of the present theory is whether it could accurately predict new findings. Thus for example it will be interesting to test whether the

Tunnel effect disappears when the dot's track was at a tangent to a hypothetical line from the fixation point.

Another illusion which can be explained by the present finding is sometimes known as Parks' Camel illusion. This is the apparent compression of figures seen moving behind a narrow slit (or anorthoscopic perception, see for example Anstis and Atkinson, 1967; Rock, 1981). In anorthoscopic perception experiments the subject learns the movement speed while viewing all the available information at or near the fovea since the slit masks everything else. The subject has to imagine the object as it moves beyond the slit to more eccentric areas, and then draw the shape of the whole object. Noting the present finding that imagined movement of objects initially slows, one might predict that the subjects estimation of the true shape of the object would be shrunken along the axis of travel. It is particularly interesting to note Shimojo and Richards' (1986) finding that peripheral viewing can lead to elongation, again as one would predict from the present results.

In conclusion, the present research has identified a non-linear eccentricity related image processing effect. This effect is consistent with an elaboration of Kosslyn's (1980) analogue model of the image buffer and the results validate some of his assumptions. The results cannot readily be explained in propositional terms and provide evidence against a strong propositional position. The results have broad and exciting implications for a number of unresolved questions in imagery and perception research, particularly in the areas of illusions, speed and distance estimation, and the nature of the imaging substrate.

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APPENDIX A. SUBJECT INSTRUCTIONS

The following general introduction was used for Experiments 1, 2 and 3:

In this series of studies we are looking at how people create and manipulate visual images. The studies are intended to extend the findings of some other important imagery studies, and to further our knowledge of how the mind encodes and transforms visual scenes. Please feel free to ask any questions at any time, and any comments or observations you may have I'd really like to hear at the end of our hour. The report of the study will be completed by July and you are very welcome to contact me or Dr. Friedman if you'd like to see it. I'll give you a handout later that has our names and office numbers.

I am going to ask you to create a visual image, or mental picture of various scenes, and imagine specific changes to

> those scenes. Do you know what I mean when I say "visual image"?

In some cases some discussion was required to reach a common understanding. The similarity between the experience of having a mental image, and actually seeing something (as opposed to imagining oneself to be seeing), was emphasized.

> This is not going to be an easy task, but what you will be asked to do is imagine the scenes and press a button in a way which I will show you to indicate when you have a clear image of the scene. Of course we have no means of knowing exactly what is happening in your mind and so I'd like to ask your cooperation in trying to make this study a success. You can best help us by making sure that your images are as clear and vivid as you can while you are doing the tasks.

Experiment 1

The following relates specifically to Experiment 1. This part was used for the practice items:

> On the screen before you are three rings arranged in a triangle. This is ring number 1, 2, 3 (clockwise around the screen). I would like you to have a good look at the rings on the screen and then try to form a mental image of the rings as they appear on the screen. What is important here is the relative locations of the three rings, rather than how the rings themselves look. Close your eyes and do that now. Tell me when you have a clear image of the three rings.

When the subject reports that he has the image:

> Now imagine all three rings, but imagine you were looking directly at the ring number "1". In other words, imagine you were looking at number "1" but could still

see the other two rings with your peripheral vision. Can you do that?

Now imagine a black dot shooting as rapidly as possible from number "1" to number "2". Your minds eye should shoot along with the dot until you are looking at number "2". OK?

Now imagine the dot shooting as fast as possible to number "3", but remember to keep your eye on the dot itself, while not loosing sight of any of the rings in your peripheral vision. OK?

And back to "2". OK?

Great. You can open your eyes now. For the next trials I'm going ask you to use these buttons. I will tell you which way the black dot is to move and you press the left button to signal when you are ready to imagine the dot moving. Immediately after you have pressed the button you should imagine the dot moving as fast as possible in the direction I told you. When you have imagined the dot to move all the way to the new position, without losing sight of the other rings, then you press the right button to stop the timer. In other words, I'll tell you where the dot is to move and when you are ready you press the left button. Immediately upon pressing the button you should imagine a black dot shooting to the target, and press the right hand button when it gets there. Remember to keep your eye on the dot but do not lose sight of any of the three rings while the dot is moving. OK?

Lastly, if you want to have another look at the figure between trials just tell me and I'll show it to you again. You may only look between trials, however. During the trials I would like you to keep your eyes closed.

At this point the practice items were begun.

Experiment 2

The general introduction to this experiment was the same as to Experiment 1.

> On the screen before you is a picture of two pins which represent players in a game with a multicolored beach ball, and as you can see, the moment the computer beeps a ball is "thrown" from one to the other. In this study you are going to be asked to imagine a number of such pins, with a beach ball passing between them in the same way.

At this point the screen was blanked and the subject was shown the three dimensional model described in the body of the thesis. The subject was told the pin identifiers (numbers or letters as in Figure 1) and asked to identify pins in a random sequence until he is quite familiar with the labeling. The subject will be encouraged to examine the model from any position, and to view the "player" pins from the perspective of the "subject" pin. Next the subject was asked to imagine the whole scene from the perspective of the "subject pin", and to look at each element in turn.

Now I want you to imagine the fixation pin is pin "B" in your image just as it is in the model right now. Please close your eyes and imagine the scene. Imagine you are looking at the fixation pin, but can see all four of the "player" pins in your peripheral vision. Please tell me when you have that image.

Great, now, without looking away from the fixation point in your image I want you to imagine a brightly patterned beach ball being thrown from pin one to pin four. Try to make your image of the moving ball as clear as possible, and to see it in your peripheral vision moving all the way through the air from pin one to pin four. Please tell me when the beach ball reaches its target.

OK. Now imagine it moving back to pin 1. Remember to keep your "eye" on the fixation pin. In addition, do not lose sight of any of the other pins as you watch the beach ball travel through the air. Let me know when the ball reaches pin 1 in your image.

Great. You can open your eyes now. For the next trials I'm going to ask you to use these buttons. I will tell you which way the ball is to move and you press the left button to signal when you are ready to imagine the ball moving. Immediately upon pressing the button you must imagine the beach ball moving through the air to the target I told you. When you have imagined the ball to move all the way to the new position, without losing sight of the other pins, then you press the right button to stop the timer. In other words, I'll tell you where the ball is to move and when you are ready you press the left button. Immediately you should imagine the beach ball thrown to the target and press the right button when it gets there. Remember, however, not to lose sight of

> any of the four pins while the ball is moving. OK?

Any questions were answered in full. Questions which referred specifically to ball speed were answered approximately as follows:

> What I want to know is how long it takes to imagine the beach ball moving between the pins, so the issue is the image, not other considerations.

Once the subject was comfortable with the task the practice items were presented as detailed in the body of the thesis. The subject was allowed to inspect the model only between trials, and specifically when the fixation point was changed.

Experiment 3.

The general introduction to this experiment was the same as to Experiment 1.

> On the screen before you is a picture of two horizontal lines which represent the

> top and bottom of an open space. As you can see, when the computer beeps a dot, representing steel ball, or rain drop, "falls" from the top to the bottom of the open space. The ball always falls between the two vertical lines.

A display detailed in the body of the thesis was presented.

> In this study you are going to be asked to imagine what you see on the screen. That is, you may look at the screen, but I want you to imagine the ball falling across the gap and tell me when your imagined ball reaches the bottom line. Have a look at the screen now, and keep your eye on this fixation point in the middle. When the computer beeps please imagine the ball falling and tell me when the ball in your image reaches the bottom.

Two such introductory trials were run.

Great! You can relax a bit while I explain the next part. The rest of the trials in this part are very similar to what you have just done. These two vertical lines will be moved between trials to some random location, and you must still imagine the ball to fall between them. That is, if the lines are at the side here, you must imagine the ball to fall here. However you must continue to look here at the fixation point in the middle while the ball is falling. Don't let your eye wander during a trial. It is also important that you don't lose sight of the ball in your peripheral vision while it is falling. Try to remain aware of where the ball is throughout its fall.

What will happen is the vertical lines will move to some or other different location, and when you are ready to imagine the moving ball, and are looking at the fixation point you must press this left button to signal you are ready.

> Immediately upon pressing the button you must imagine the ball to start falling. As soon as the ball reaches the bottom you must press the right button to stop the timer. OK?

Any questions were answered and the 14 practice items were presented.

> OK. Now the next ones are pretty similar with one exception. In these the size of the gap on the screen is going to change. Sometimes it will be larger than it is now and sometimes smaller. Your task is still to imagine the ball falling across the gap that you see, however big it is, in the location indicated by the vertical lines. OK? Try a few.

Six additional practice items were presented, two at each of the three ball drop widths (2, 3, and 5 degrees).

At the completion of the practice items the remaining items were presented, blocked as indicated in the body of the proposal.

Table 5

Experiment 1: Image Scanning Times.

	VVIQ Group 1		VVIQ Group 2		VVIQ Group 3	
	Mean	SD	Mean	SD	Mean	SD
Horizontal Figure						
Inwards	561.27	249.91	653.94	251.93	599.67	293.36
Outwards	574.17	236.28	604.88	227.19	563.60	254.49
Middle	567.38	236.72	637.75	230.40	575.19	270.06
Vertical Figure						
Inwards	581.54	262.79	668.83	241.98	567.63	283.94
Outwards	590.17	248.48	648.90	263.78	527.79	234.05
Middle	603.60	265.81	691.00	264.51	561.77	284.71
Square Figure						
Top	687.77	331.23	705.90	229.77	648.03	330.03
Side	671.49	307.99	705.71	207.08	653.93	330.53
Diagonal	773.36	418.59	797.90	296.89	761.91	460.08
Horizontal Stepsize						
5 degrees	567.60	238.89	632.19	235.19	579.49	270.15
10 degrees	826.76	409.94	960.80	491.89	756.95	415.74
15 degrees	1009.44	567.93	1198.06	732.76	877.77	528.53
Vertical Stepsize						
5 degrees	591.77	257.15	669.58	254.76	552.40	265.41
10 degrees	837.66	404.80	985.09	460.01	740.08	397.69
15 degrees	1027.83	579.49	1162.77	666.11	853.90	496.19

Table 6

Experiment 2: Imagined Ball Movement Times.

Movement Direction		Eccentricity (degrees) 3	5	7	9	11	13
		VVIQ Group 1					
Inward Movement							
	Mean	857.42	902.33	922.33	854.88	934.88	866.04
	SD	495.53	553.95	549.47	433.73	484.35	428.33
Outward Movement							
	Mean	789.46	929.13	941.75	883.71	952.92	924.25
	SD	399.66	514.26	532.62	513.84	550.48	507.03
		VVIQ Group 2					
Inward Movement							
	Mean	704.67	777.58	724.71	720.75	762.58	740.33
	SD	340.99	287.54	297.47	336.51	350.48	321.94
Outward Movement							
	Mean	693.29	746.75	773.25	752.04	750.08	757.25
	SD	330.94	286.06	309.73	324.94	312.50	300.85
		VVIQ Group 3					
Inward Movement							
	Mean	903.75	949.75	888.58	898.25	878.83	876.83
	SD	285.81	283.03	334.56	356.63	393.15	362.80
Outward Movement							
	Mean	846.58	937.46	968.08	878.88	840.71	866.67
	SD	261.81	296.75	317.23	412.85	366.13	446.58

Table 7

Experiment 3: Imagined Drop Times.

Eccentricity (degrees)	Drop Distance					
	2 Degrees		3 Degrees		5 Degrees	
	Mean	SD	Mean	SD	Mean	SD
			VVIQ Group 1			
1	1565.00	840.670	2177.08	1111.99	2970.41	1441.39
3	1579.25	872.650	2257.08	1140.90	2941.50	1370.21
5	1710.58	928.556	2209.58	1125.53	2893.16	1451.41
7	1699.16	954.408	2357.25	1274.72	3026.33	1463.21
9	1770.58	967.933	2247.00	1149.88	2903.33	1512.90
11	1789.50	1079.72	2292.00	1231.23	2891.08	1474.63
13	1735.25	1008.35	2171.91	1219.76	3042.25	1605.16
			VVIQ Group 2			
1	1111.08	607.012	1332.58	662.015	1616.00	849.449
3	1123.91	534.248	1342.91	720.588	1743.50	1016.44
5	1124.00	632.455	1388.83	732.314	1710.16	962.960
7	1140.58	650.626	1414.75	786.912	1657.83	972.961
9	1115.66	617.663	1419.66	788.629	1708.75	1002.61
[illegible]	1139.66	566.429	1381.75	778.947	1623.41	903.870
[illegible]	1117.66	586.590	1311.25	687.350	1655.33	933.822
			VVIQ Group 2			
1	1147.00	311.317	1419.41	326.522	1731.50	370.283
3	1128.08	296.492	1428.75	289.770	1840.25	443.867
5	1169.66	230.571	1478.50	327.048	1819.16	330.396
7	1068.50	264.622	1433.08	330.816	1799.50	270.496
9	1090.16	228.538	1387.16	280.713	1843.08	391.966
11	1149.83	302.499	1406.58	234.115	1831.75	413.229
13	1091.25	317.741	1387.33	275.488	1806.00	409.940

Table 8

Characteristics of Jolicoeur and Kosslyn's (1985) Figures

Route From	Route To	Distance	Eccentricity
lake	tree	2.1	7.36666
well	hut	3.4	8.88333
hut	tree	4.2	8.02499
well	tree	4.5	7.99166
hut	lake	5.1	8.25833
well	lake	6.4	8.22500
lake	beach	7.0	[illegible]
rock	grass	7.8	[illegible]
tree	grass	8.5	[illegible]
tree	beach	8.9	[illegible]
well	grass	9.3	[illegible]
lake	grass	9.8	9.05833
hut	beach	10.4	10.6499
hut	grass	11.8	9.71666
well	beach	12.9	10.6166
tree	rock	14.6	11.2333
lake	rock	15.2	11.4666
beach	grass	15.9	11.4499
well	rock	16.6	12.0916
hut	rock	18.6	12.1250
beach	rock	19.2	13.8583

Table 9

Jolicoeur and Kosslyn's (1985) Experiment: Imagined Dot Movement Times

Route		Experimental groups							
		Group 1		Group 2		Group 3		Group 4	
From	To	Mean	SD	Mean	SD	Mean	SD	Mean	SD
lake	tree	871	170	1017	220	1004	267	1034	194
well	hut	983	237	1172	343	1004	152	1143	215
hut	tree	983	225	1137	259	1053	224	1182	283
well	tree	1019	253	1111	241	1065	282	1150	376
hut	lake	1011	303	1092	243	1131	298	1149	251
well	lake	1099	319	1220	328	1115	202	1245	415
lake	beach	1071	380	1227	371	1132	374	1228	380
rock	grass	1047	349	1238	282	1116	313	1284	307
tree	grass	1177	349	1338	416	1179	356	1347	399
tree	beach	1084	341	1295	328	1124	296	1172	351
well	grass	1206	458	1369	269	1170	346	1404	367
lake	grass	1245	576	1281	329	1252	348	1361	369
hut	beach	1117	440	1213	367	1099	367	1243	459
hut	grass	1116	434	1360	349	1174	318	1345	453
well	beach	1167	399	1312	381	1160	236	1253	359
tree	rock	1221	496	1333	423	1248	409	1397	490
lake	rock	1193	466	1337	429	1233	310	1333	411
beach	grass	1186	557	1302	397	1271	512	1325	337
well	rock	1190	458	1378	497	1251	365	1410	480
hut	rock	1231	438	1368	477	1226	338	1419	440
beach	rock	1145	474	1348	468	1148	395	1345	464