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Scanning visual mental images: A window on the mind

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Abstract

The process of mental scanning corresponds to the systematic shifting of attention over visualized objects. The first part of this article focuses on the role of mental scanning as an empirical method to assess the structural properties of the representations that underlie visual mental imagery. One theory of imagery posits that the metric properties of the surfaces of objects are made explicit in visual images. If so, then the time to scan across imaged objects should increase linearly with the distance scanned, and such results have been reported in a number of experiments. However, these results proved controversial. Various alternative accounts were proposed, and new studies conducted. The present review shows that the alternative accounts were not compelling, and that results from image scanning studies are best interpreted as reflecting the metric properties of imagery representations and also showing that imagery uses mechanisms that are used to encode and interpret objects during perception. The second part of this article focuses on the use of image scanning to examine whether verbal des-

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criptions may be used to construct images with structural properties similar to those of images of previously seen objects. Newly constructed images have been shown to possess a structure very much like the structure of representations that arise from visual perception. Moreover, the scanning technique has been used to study which properties of descriptions allow them to be converted easily into images. Finally, the article considers the use of the mental scanning paradigm in neuroimaging studies. By examining the neural foundations of mental scanning, researchers are in a good position not only to learn more about imagery, but also to discover more about the roles of particular brain mechanisms.

Key words: Mental scanning, visual imagery, visual perception, verbal descriptions, neuroimaging.

INTRODUCTION

Historically, mental imagery has played a major role in most theories of mental events. Thinkers spanning the ages from the ancient Greek philosophers, to the British Associationists, all the way up the founders of experimental psychology put mental imagery at the center of their theories (e.g., see Boring, 1950). However, in particular in Anglophone countries, imagery was banished from scientific psychology by the Behaviorists, and was neglected for many years. As the limits of behaviorism became clear, the study of the mind again moved to the center of the field of psychology. However, it has proven surprisingly hard to reintegrate the study of mental imagery back into the core of psychology. One of the unfortunate legacies of behaviorism has been a deep suspicion about private mental events. Other mental faculties, such as memory and language, have clearly observable behavioral consequences (e.g., one can say words aloud). Imagery, in contrast, is less obviously connected to events outside the skin. Thus, the invention of behavioral methods to study imagery was a major prerequisite not only to understanding the phenomenon, but also to making it fully respectable once again.

In this article, we review one method (in fact, a collection of related methods) that allows us to observe the behavioral consequences of using imagery. This method relies on the analysis of response times and treats them as analogous to the streak in a cloud chamber created by a cosmic ray: One does not see the particle directly, but rather witnesses its footprints. Similarly, one can use response times to track the processing of a mental image, with distinctive patterns of times corresponding to the unique footprint of the use of imagery.

The method reviewed here is *image scanning*. Image scanning is not the simple act of extracting information from a visualized pattern. For example, consider the answers to the following questions: What shape are a cat's ears? Which is darker green, an avocado or a pea? Which hand did Napoleon tuck into his vest? In each case, you probably experienced visualizing the object to answer the question. In these examples, however, you probably immediately focused on the parts of the object of interest, the ears, fruit, or hand. Now compare those kinds of images to the one you experience when you answer the following question: How many windows are in your living room? When answering this question, many people report that they visualize the room and then mentally shift their attention over the walls, counting the windows. It is this systematic shifting of attention over an imaged object that constitutes image scanning. The mere fact that one examines an image does not imply that image scanning was used; one must also shift attention across the object.

Why is image scanning important? It is primarily important because of what it can tell us about the mechanisms used in imagery, at least some of which may also be used in vision proper. Image scanning has been used to illuminate three aspects of these mechanisms in particular.

Image structure. In the earliest image scanning experiments, the time to shift attention over an imaged object was used as a kind of "mental tape measure". In these studies, image scanning was used as a way to study the properties of the representation that was being scanned, as a way to study the *structural properties* of images. The strong claim was made that image representations depict information, and hence that metric properties of the surfaces of objects are made explicit in images. This view predicted that the time to scan across imaged objects should increase linearly with the distance scanned, provided that the rate of scanning itself and distance of the object from the viewer were held constant. As is reviewed below, such results were reported.

Image creation. Once image scanning methods were developed, they then were used to assess the consequences of different ways of creating an image. In particular, researchers investigated the ways that images of separate objects can be composed, and used scanning to examine whether *verbal descriptions* may be used to produce an accurate portrayal of a pattern. If images could be created accurately from such inputs, then one should find linear increases in time to scan increased distance over the imaged patterns. In particular, mental scanning was used to assess whether the images of objects constructed from purely verbal descriptions exhibit properties of the visual images reconstructed from memories of previously seen objects. Such structural properties were found in images created by subjects from descriptions of objects that they had never seen before.

Images in the brain. The most recent use of scanning is as a behavioral assay to plumb the functions of different regions of the brain. In these studies, subjects scan images while brain activity is assessed. Thus, the brain-bases of scanning can be inferred by observing which areas are relatively more active while the task is performed. Moreover, the behavioral results can be related to the brain activation, providing another way to understand the function of particular brain areas. This approach has just been developed recently, and appears to be a promising method for discovering the detailed mechanisms of visual imagery.

The main purpose of the present article is to review findings and arguments for the role of the mental scanning paradigm as a source of information on visual imagery. Mental scanning, as other paradigms developed in the context of imagery research, was designed to reveal aspects of imagery that previously were only accessible to introspection. We show here that the mental scanning paradigm is a source of valuable information on the structural properties of visual images and their status as quasi-pictorial internal representations. We also argue that the paradigm has a still more general value because it can be used to study the properties of novel types of images. The paradigm, thus, widens the empirical basis of our theoretical view of imagery. Lastly, by connecting the mental scanning paradigm to brain studies, we try to relate theories of imagery to the cerebral structures that underlie this process.

THE STRUCTURAL PROPERTIES OF VISUAL MENTAL IMAGES: EVIDENCE FROM THE MENTAL SCANNING PARADIGM

In this section, we review the use of image scanning as a tool for studying the structure of imagery representations.

Measuring mental scanning

It is important to recall the theoretical context in which the mental scanning paradigm was devised. The original Kosslyn (1973) study was motivated by the simple idea that if objects in mental images are like pictures, they should have spatial properties, which should allow them to be scanned like actual pictures. However, it seemed clear at the time that mental images are not actual "pictures in the head", and thus the paradigm came to be developed within a theory of imagery (cf. Kosslyn, 1980; Kosslyn, Pinker, Smith, & Shwartz, 1979; Kosslyn & Pomerantz, 1977). According to this theory, images are short-term memory displays that are generated from more abstract representations in long-term memory. These displays are patterns within a "visual buffer" which functions as if it were a coordinate space. This "space" is not an actual physical one but is rather a functional space, defined by the way processes access the structure. The visual buffer has an innately determined and fixed organization. It has a limited extent and a limited resolution (highest at the center and decreasing toward the periphery). All image representations in the buffer have the property that every part of the representation corresponds to a part of the represented object in such a way that the relative distances among parts of the object are preserved by the distances among the corresponding parts of the representation. In contrast to verbal or propositional representations, images *depict* information by a semantics of resemblance. The structural analogy between images and the represented objects confers particular functional properties. Finally, interpretive mechanisms (for "inspecting" the imaged object) and transformations (for altering the shape) operate on these internal displays.

When this theory was developed, specific experimental situations were devised to assess the representational properties of images. Images are conceived of as "quasi-pictorial", in the sense that they are thought to *depict* information rather than *describe* it in a discursive way. In addition, the images people experience are not epiphenomenal concomitants of more abstract, nonpictorial processing. A family of experiments were then conducted to address the view of "image-as-epiphenomenon". These experiments were motivated primarily by the assumption that images depict information in a spatial medium. One consequence of a quasi-pictorial image is that if images are functional, spatial extent should affect information processing when images are used. In contrast, if quasi-pictorial images are not functional, their spatial properties would not affect information processing.

The idea that the internal structure of an image parallels the spatial structure of its referent allows us to make specific claims about image processing. In particular, if images depict spatial extent, they should preserve relative metric distances between portions of objects or parts of objects. If so, time to retrieve features of an image would be expected to be a function of spatial distance scanned during search. Specifically, more time should be required to scan longer distances across images. The most simple image scanning paradigm was developed by Kosslyn (1973). He asked subjects to memorize drawings prior to the study, and then to close their eyes and visualize a particular drawing while mentally "fixating their gaze" at one end of the imaged object. Shortly thereafter, the subjects (with eyes closed) heard the name of a possible feature of the imaged object (e.g., if it was a boat, "*porthole*"). They were to "look for" the named part on the imaged object. If they could find it, they pressed one button; if they could not find it, they pressed another button. They were told to respond as quickly and accurately as possible. The distance from the point of focus to the queried property was varied from trial to trial. The results showed that the farther a property was from the initial focus point on the imaged object, the longer it took to "see" it in the image. This finding thus provided support to the claim that distance is represented in visual images of objects.

However, the value of these results was criticized because in this experiment the distances scanned were not independent of the number of items that were scanned over in the image. This was a difficulty for the theory because the apparent effects of distance could be explained by alternate theories that reject the quasi-pictorial interpretation of images. In particular, if one assumes that activating an internal representation consists of activating networks of propositions, the number of links in the network that must be traversed before reaching the representation of the searched property predicts the time required to shift activation to this representation. Such interpretation was developed by Lea (1975), from the results of an experiment in which subjects learned a circular array of objects by using imagery and later had to evaluate the relative locations of the objects in the array. Subjects were given the name of one object and asked to name the first, second, or *n*th item in a given direction. The results showed that response times did not depend on the actual distance separating a pair of objects in the array, but rather on the number of intervening items between the initial focus point and the target.

In order to eliminate the confounding that limited the interpretation of the original results, Kosslyn, Ball, and Reiser (1978) designed experiments involving objects where the number of items scanned over during mental scanning was controlled, or where no intermediate items were present along the distances scanned by the subjects. In Experiment 1, subjects had to scan visual images of three-letter linear arrays. In scanning to a named target letter, they had to traverse one of three different distances and pass over zero, one, or two intervening letters. Arrays were constructed in such a way that the number of letters and the distance scanned were varied independently. The results showed that the time to scan to designated letters increased linearly with distance and, independently, with the number of letters scanned over. This was a clear indication that distance *per se* affected scanning times, and that the effects of distance previously observed were not simply an artifact of how many items were scanned over by the subjects.

In another experiment (Experiment 2), subjects were invited to learn the map of an island that contained seven objects (e.g., a hut, a tree, a rock; see Figure 1). These objects were located such that there were 21 distinct distances among them. Subjects were first asked to memorize the map. They were instructed to study it, close their eyes and form an image, and then compare the image with the actual map. This procedure was repeated until the subjects felt they had an accurate image of the map. The subjects then drew the locations of the seven objects on a blank map, and were invited to compare their drawings with the original. The draw-and-study procedure was repeated until each location in the drawing was within a criterion distance of its actual position.

Once the subjects had memorized the configuration and the precise locations of objects, the experiment proper began. On each trial, the subjects closed their eyes, visualized the map, and started by focusing on a named object (for instance, the hut). Upon hearing the name of a second object (for instance, the tree), the subjects had to mentally scan the distance that separated the two objects and to indicate (by pushing a button) when scanning was completed. The subjects' response interrupted a clock, which indicated the time taken to perform the mental scanning on each trial. On half the trials the subjects could find the second named object, but on the other half of the trials the second named object was not present on the map. When this occurred, the subjects pushed another button, indicating that the object was not part of the original configuration. To encourage the use of mental scanning, the instructions stated that subjects should image a little black speck zipping in the shortest straight line from the first object to the second. The speck was to move as quickly as possible, while still remaining visible. In a second condition (Experiment 3), subjects were asked to "zoom in" on the first location (the one they focused upon) and simply to "look for" the second, without using the flying speck. In both conditions, the analysis focused on the first type of responses, when the subjects could in fact find the second named object.

Figure 1. The map used in Kosslyn, Ball, and Reiser's (1978) experiments.

The main finding from both conditions of this experiment was that scanning times increased linearly with increasing distance (Figure 2); indeed, a large positive correlation between times and distances was obtained. In a control condition (Experiment 3), subjects who had learned the same geographical configuration were asked to focus on a named object and to decide — without referring to the image — whether the second name corresponded to an object on the map. In this condition, no correlation was found between response times and distances.

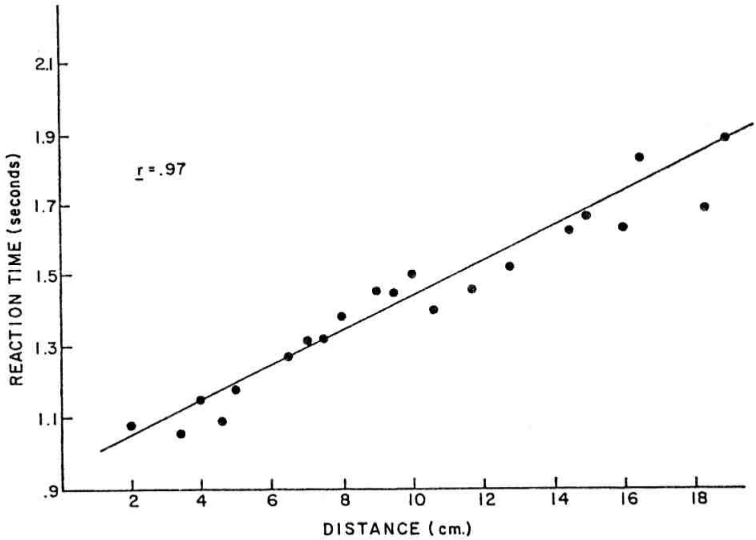


Figure 2. Response time (sec) as a function of scanning distance (cm) (Kosslyn, Ball, & Reiser, 1978, Experiment 2).

In the last experiment (Experiment 4), Kosslyn et al. (1978) invited subjects to memorize pictures of three schematic faces, which had eyes one of three different distances above the mouth. Subjects then visualized each face at one of three subjective sizes. When subjects scanned from the mouth to the eyes (in order to classify their color), scanning times were longer for larger amounts of separation between the mouth and the eyes. In addition, times increased when subjective size (and hence overall distance) increased. The latter result is of special interest inasmuch as it cannot be ascribed to the effects of distance on initial encoding because subjective size was manipulated long after the encoding of the pictures.

At about the same time, Beech (1979) provided similar evidence that image scanning times increased as a function of increasing distance. Subjects were presented with arrays containing four circles with digits within the circles. There was a central circle, and the other circles were arranged diagonally from the central one at different distances. An array was presented for 7 seconds, and 4 seconds after the offset of the array, a digit was presented through headphones. The subjects were required to indicate by pressing a button whether the digit was present in the previously presented picture. They were instructed to maintain an image of the picture as if it were still on the screen. The subjects used the central circle as the focus point in the array and when they heard the digit, they had to "look" outward from the point on which they were fixating. The results showed a monotonic increase in reaction times for correct responses as a function of the absolute distance scanned. By contrast, there was no systematic increase in reaction times as a function of the relative distance scanned. The experiment thus demonstrated that the subjects were scanning an imaginal representation of absolute distances. The discussion of the results contrasted an interpretation in terms of operations within an imaginal representation which involves analogical processing, and another in terms of operations on a propositional representation underlying the image (cf. Wilton, 1978).

All these experiments addressed mental scanning across images of two-dimensional objects. A study by Pinker and Kosslyn (1978) investigated the representation of three-dimensional space in mental images. The subjects studied a box in which four or six tiny objects were suspended at various positions in space. They later were asked to close their eyes, imagine the box, and scan between pairs of objects in the image. Chronometric measures similar to those collected in Kosslyn et al.'s (1978) experiments revealed that the time necessary for subjects to scan between two objects was proportional to the distance between them in three dimensions. Furthermore, scanning times more closely reflected actual three-dimensional distances than the distances between the objects in two-dimension planar projections. Lastly, when subjects were instructed to mentally move an object, then to scan between this object and another one, the scanning time was proportional to the new distance between that object and the other one. Further studies based on measures of mental scanning confirmed that subjects also could "see" the planar projection of objects in three-dimensional scenes from any number of viewing positions, including ones never actually experienced (cf. Pinker, 1980; Pinker & Finke, 1980).

The findings of Kosslyn et al. (1978) and Pinker and Kosslyn (1978) were taken to reflect the structural isomorphism of visual mental images with corresponding objects. They were clearly compatible with the assumption that if the mental scanning effect is obtained with an image, it is because it incorporates the metric information present in the original object. No claim was made that visual images themselves have spatial extent, or that they occupy metrically defined portions of the brain. The idea was that the mechanisms that interpret visual images operate on a cognitive entity that incorporates the spatial characteristics that were processed during perception. It is clear from the control condition reported above, where the typical chronometric pattern was not observed, that subjects can store and access information represented in other forms than images, but when information is embodied in a visual image, this representation possesses the specific property of representing metric distance, and this property affects real-time processing of images.

In the context of the discussions developing during this period, the first results obtained with the mental scanning paradigm provided empirical responses to the theoreticians who claimed that mental images are not a functional component of the human mind, and that the representations underlying image processing are of the same sort as those that underlie more abstract forms of cognition (cf. Anderson & Bower, 1973; Pylyshyn, 1973). On the contrary, these findings provided support for the view that the processes operating in imagery have specific characteristics that are distinct from those operating in abstract thought.

Task demands and cognitive penetration

Among the objections to the mental scanning experiments, the first one consisted of claiming that the results do not bear on the *properties* of imagery because they are contaminated by *demand characteristics* of the experimental situation (Mitchell & Richman, 1980; Richman, Mitchell, & Reznick, 1979). The general argument was that subjects deduce the purpose of the experiment in which they are taking part, and they control their responses in order to provide the results that they think the experimenter is expecting. In this case, the subjects may believe that it will take longer to scan longer distances and so they delay responding when longer distances should have been scanned in order to comply with the experimenter's expectations. A variant of this criticism is that scanning instructions are understood by subjects as referring to physical movement. Consequently, mental scanning would be nothing else than mental simulation of motion, which might explain that "more motion" results in longer response times.

Other researchers appealed to yet another factor to explain the mental scanning findings (notably, Pylyshyn, 1981). According to this view, the results simply reflect the *tacit knowledge* subjects have about visual processes. Although "tacit belief" would have been a better term, "tacit knowledge" was adopted in the literature to refer to subjects' unconscious belief, which may or may not be correct. In particular, most people may believe that visual scanning between successive fixations takes more time when distances are greater between fixation points, and hence that knowledge guides their responses in the image scanning task. A variant of this argument is that people know that if the speed of a moving object is held constant, it will take more time for the object to traverse the distance between two distant points than two near ones. Because they also know that it takes more time to visually scan longer physical distances, people will conform their response times to their knowledge of the physical laws that relate speed, time, and distance. Pylyshyn (1981) developed this line of argument and used it to contest the idea that images are a fundamentally different form of internal representation, distinct from that which underlies language. Instead, he favored the view that images are merely a species of a single form of representation used in all cognitive processing. Pylyshyn also contested that accounting for imagery phenomena requires one to postulate the notion of "analogue processes" (such as those that operate in a visual buffer), thus refuting the alleged spatiality of images.

Pylyshyn (1981) argued that imagery processes are *cognitively penetrable* because they can be altered by beliefs, goals, expectations, or knowledge. If the form of an image transformation function can be altered by changing the subject's interpretation of the task, then the explanation of the function must involve such constructs as beliefs, or tacit knowledge, rather than the intrinsic properties of a representational medium (such as depictive patterns in a spatial visual buffer). Pylyshyn agreed that even if a process is cognitively penetrable, it may still be analogue. But his ultimate argument was that the way in which images are processed (i.e., transformed in mental rotation or scanned in mental scanning) should not be attributed to intrinsic properties of the visual buffer. He claimed that, in mental scanning and mental rotation, image processing results in specific chronometric patterns because subjects understand the task as requiring them to simulate witnessing of real events. Functions that are cognitively penetrable should thus be accounted for by computational cognitive processes rather than by the properties of depictive images.

The first experiment that attempted to assess possible effects of experimental demand characteristics in a mental scanning task was conducted by Richman et al. (1979). They asked subjects to memorize a map similar to the one used by Kosslyn et al. (1978), and then to mentally scan between all pairs of objects. Richman and his colleagues designed the study to assess whether the use of images can be superseded by verbal codes when verbal information provided on the map is inconsistent with spatial distances. In order to do so, two roads equally long (from the hut to the well and from the hut to the tree) were labeled with a road sign stating "*20 miles*" in one case and "*80 miles*" in the other. When the subjects imagined the map and scanned between objects, they required more time when scanning larger distances, but their scanning times also were significantly longer for the distance labeled "*80 miles*" than for the distance labeled "*20 miles*". This result suggested that subjects altered their responses to conform to the mileage information provided on the map.

There is no doubt, indeed, about the capacity of subjects to alter their response times if they are so motivated (either by external or self-generated demands). This is why mental scanning experiments typically include post-experimental questionnaires, which are included so that data can be discarded from subjects who might have deduced the purpose of the experiment and/or reported difficulty in following imagery instructions (cf. Kosslyn, 1973; Kosslyn et al., 1978). Nevertheless, one difficulty with Richman et al.'s (1979) argument is that it was based on data collected in an experiment including strong task demands, and the experiment did not demonstrate that demand characteristics are responsible for the distance effects in other image scanning conditions.

In a second study, Richman et al. (1979) asked subjects to predict the results of an experimental procedure that was described to them, namely the procedure used in their first study. "Pseudoexperiments" are usually considered as a means of measuring the demand characteristics of a procedure. The similarity between the results of a pseudoexperiment and those of the actual experiment is thought to reflect the extent to which subjects are able to perceive and respond to the experimental hypotheses (cf. Orne, 1969). In this study, subjects were asked to estimate what they thought their response times would be if they had participated in the scanning experiment. The results showed that subjects predicted longer scanning times for the more distant than for the less distant objects. In addition, they predicted longer response times for the distance labeled "*80 miles*" than for the (same) distance labeled "*20 miles*".

From these findings, Richman et al. (1979) argued that mental scanning results may be due to demand characteristics inherent in the paradigm and therefore may not be a function of the spatial properties of visual images. However, subjects' responses in this pseudoexperiment do not imply that they attend to the relations between distance and time in the mental scanning experiment itself, nor that they manipulate their response times in accordance with this relation. Virtually all subjects, in fact, deny doing this. It is possible that subjects would predict experimental data in pseudoexperiments, regardless of how they would behave in the experiment itself. Kosslyn et al. (1979) tested this possibility by describing a typical mental scanning experiment to subjects, and mentioning that some objects were highly associated semantically (e.g., tree and grass) and some others were not associated (e.g., hut and rock). When subjects were required to estimate their response times for these two conditions in a real experiment, they predicted shorter scanning times between highly associated items, an effect which in fact is not obtained in mental scanning experiments. In another pseudoexperiment, the same experiment was described, but the experimenter mentioned that objects which are close together in the image may be difficult to "see" distinctly in the image. This suggestion was reflected in the response times predicted by the subjects, with *shorter* times predicted for *longer* distances, that is, the opposite of the results obtained in mental scanning experiments (cf. Kosslyn et al., 1979).

Mitchell and Richman (1980) conducted a further pseudoexperiment in a more complicated design involving the map used by Kosslyn et al. (1978). In this study, estimated scanning times increased as a linear function of increasing inter-object distance on the map. The correlation between distance and time was produced by subjects independently of an image-scanning procedure. Mitchell and Richman took their findings as a confirmation that experimental demand characteristics may be operating in the mental scanning paradigm. Other investigations of people's knowledge about images, however, did not confirm that subjects were so prone to predict the results of image scanning experiments. In an investigation of non-scientific knowledge about images, Denis and Carfantan (1985) presented 148 undergraduates with brief descriptions of classic imagery experiments and asked them to guess the typical results. It was found that 9.5% of respondents were ready to believe that more time is required to scan longer distances in imagery, whereas 58.8% did not expect scanning times to be proportional to the distance scanned. The remaining subjects (31.8%) claimed that they had no idea about such relationship. The opacity of mental scanning and other imagery phenomena (such as mental rotation or the effect of image size on the verification of object's properties) turned out to be highly resistant. In a subsequent study where subjects were required to mentally simulate image scanning before responding, there was no increase of the rate of their correct predictions (Denis & Carfantan, 1986). When subjects were provided with a detailed description of Kosslyn et al.'s (1978) Experiment 2, the rate of their correct predictions still remained clearly below chance level, i.e., 50% (Denis, 1991b). Only exposure to detailed experimental report and argumentative text about imagery was able to significantly increase undergraduates' willingness to declare that scanning takes longer for larger distances (Denis & Carfantan, 1990). Thus, if imagery phenomena were nothing more than the reflection of highly available tacit knowledge, one should reasonably expect that people could predict and/or give accurate accounts of imagery processes on the basis of this knowledge. The low percentage of people ready to venture a guess that distance determines mental scanning time is difficult to reconcile with a strong tacit knowledge account.

A further study by Goldston, Hinrichs, and Richman (1985) bears on this issue. They conducted a typical mental scanning experiment and showed that subjects who were told that scanning times would increase with longer distances did produce larger correlations between time and distance than did subjects who were told that times would increase with shorter distances, that they would not differ, or that the experimenter had no expectations in this respect. Thus, manipulating subjects' expectations apparently resulted in altering the time/distance relationship. However, the fact remained that in all conditions scanning time increased linearly with increasing distance. This increase in time with distance is the critical property of these experiments. It is this increase that is supposed to reflect the depictive nature of the image representation itself.

In a similar vein, Intons-Peterson and Roskos-Ewoldsen (1989) investigated whether the sensory-perceptual features of objects would affect how people used images of those objects. Subjects estimated the time it would take them to mentally transport three objects of different weights (a balloon, a ball, and a cannonball) between pairs of locations on a campus. The mental-transport times increased as the hypothetical weight of the object increased, which suggests that images may incorporate sensory attributes of the represented objects. However, again, increased distances systematically resulted in increased scanning times. Thus, even though the *rate* of scanning can be affected by demand characteristics and can be varied intentionally, such effects do not challenge the claim that depictive images are scanned and that scanning time is proportional to distance scanned.

Pylyshyn (1979, 1981) has offered a criterion for deciding whether or not a cognitive process is "primitive" (i.e., a basic building block that operates independently of others). The test is that if a process can be influenced by other cognitive factors, such as the person's knowledge, beliefs, or interpretation of the situation, then it cannot be a primitive process but must decompose into parts that can interact with the symbol structures representing one's knowledge, beliefs, and so forth. However, there are no grounds for assuming that a cognitive process can only be explained if the explanation refers to primitive information processes (cf. Kosslyn, 1981; Kosslyn et al., 1979). In Kosslyn's theory, because the properties of the visual buffer are innately determined, knowledge, beliefs and intentions should not alter the spatial structure of the visual buffer. On the other hand, the processes involved in image construction and image transformation are not shared with perception. To be useful in cognition, for instance to serve in the higher reasoning processes, imagery should be influenced by one's knowledge, beliefs, and so forth. Thus, some aspects of imagery processing should be "primitive", and some should not be.

One version of the tacit knowledge account posits that in imagery experiments, people use their tacit knowledge of visual perception to produce the results. According to this account, subjects participating in tasks calling for imagery would not necessarily make use of analogue images, but rather would consider how the object or situation they are imaging would look if they were actually seeing it. This assumption, however, has difficulty in accommodating the many cases where imagery and perception share counterintuitive properties, including properties that people are unaware of in perception, such as in experiments on color aftereffects, the size of fields of resolution, or the "oblique effect" (cf. Finke, 1980, 1985; Kosslyn, 1981; Kosslyn, Sukel, & Bly, 1999).

Experimenter expectancy effects

In many psychology experiments, experimenters may have an opportunity to provide (consciously or unconsciously) subjects with cues that lead them to produce the expected results. Some researchers have tried to explain the mental scanning results in terms of such *experimenter expectancy effects*.

In one experiment, Intons-Peterson (1983) asked four experimenters to test subjects on imaginal and perceptual scanning of maps, and gave them different "predictions" regarding the results they should obtain. Two experimenters were led to expect that subjects would scan an imaged map faster than a perceived one, and the other two experimenters were led to expect that subjects would scan a perceived map faster than an imaged one. Intons-Peterson expected that the speed of imaginal scanning would be faster than perceptual scanning when the experimenters believed that these results would be found, whereas the converse should occur when the experimenters held the opposite belief. The results showed that the predictions given to the experimenters affected the results. Scanning times were generally longer (i.e., the intercept value of the function was higher) in the imagery condition when the experimenters expected image scanning to take longer than perceptual scanning, but there was no difference in scanning times when the experimenters believed the opposite. In all conditions, however, response times increased proportionally when distance increased, and the rate of scanning (i.e., the slope of the function) was the same. Thus, the experimenters' expectancies apparently affected the intercept of the scanning function, but no evidence was found that the slope or the shape of the function was affected.

These results were considered by Jolicoeur and Kosslyn (1985) to have no direct theoretical implications for imagery theories, since all theorizing focused on the slope and shape of the scanning function rather than on the intercept. Jolicoeur and Kosslyn conducted several experiments to discover whether expectancy effects may cause the typical linear increase in time with distance scanned. In their first experiment, two experimenters were recruited to test subjects in a mental scanning experiment using the same map of fictitious island as in Kosslyn et al.'s (1978) experiment. The experimenters were led to expect a U-shaped function, with the longest times for the shortest and the longest distances. For the short distances, experimenters were told that subjects would have difficulty in discriminating among the objects that were cluttered together, whereas for the long distances, more time would be required to scan. Contrary to the expectations of the experimenters, the results were identical to those of the original experiment, with times increasing linearly with increasing distance.

In the second experiment, Jolicoeur and Kosslyn tested whether the experimenters' expectations would affect overall scanning times (the mean of response times) and/or the amount of increase with distance scanned (the slope). Four experimenters tested subjects in a mental scanning experiment in which two versions of the map were used, a black-and-white and a color version. The experimenters were led to expect different combinations of results in terms of slope and overall mean of the scanning function. In fact, the experimenters' expectations did not affect either the slopes or the relative rates of scanning. As in the Intons-Peterson (1983) study, the experimenters' expectations failed to affect subjects' scanning behavior. The third experiment by Jolicoeur and Kosslyn replicated more closely the conditions in Intons-Peterson's experiment by examining scanning in an imagery and in a perceptual condition. Again, the experimenters' expectations about the relative rates of scanning and relative overall means did not affect the results. Thus, the findings from these experiments converged in showing that the experimenters' expectations did not affect the actual scanning rates. The strong similarity between these findings and the earlier image-scanning data undermined Intons-Peterson's claim that the effect of distance on scanning time is due to experimenter expectancy effects.

Improving the mental scanning paradigm

Although mental scanning results are unlikely to be a simple consequence of task demands, tacit knowledge, or experimenter expectancy effects, the potential influence of these factors should be considered seriously and studies should be designed to minimize such influences. Ideally, three conditions should be fulfilled to prevent such effects on mental scanning. First, the responses given by subjects should not be shaped or biased by any prior knowledge. Second, no explicit imagery instructions should be given by the experimenter, and conditions should be created such that if subjects form and scan images, they do so spontaneously. Third, the subjects should not be led to suspect that the experimenter is interested in time, distance, and their relationships; consequently, they should be unlikely to try to simulate phenomena that they know to be true from their observation of physical variations.

These conditions were first achieved in an experiment conducted by Finke and Pinker (1982). In this experiment, subjects inspected a pattern consisting of four dots. Then, the pattern was removed, and an arrow was shown, pointing from an unexpected location in an otherwise blank field (Figure 3). The subjects' task was to judge as quickly as possible whether or not the arrow would have pointed at any of the dots if it were superimposed over the previously observed pattern. The subjects were never instructed to form or scan visual images, and no mention of physical motion of any sort was made. However, they would very likely have to scan along an extrapolated line in an image of the configuration in order to perform the task. As a matter of fact, the majority of subjects reported having done so in order to perform the task, and the time they needed to decide whether the arrow would point at a dot increased linearly with the distance to the dot (Figure 4). This result is important because the judgments of direction were required from unexpected locations, which means that (in contrast to the previous mental scanning studies) the subjects could not have retrieved explicit encodings of inter-point distances and then delayed their responses by proportional amounts. The Finke and Pinker (1982) results therefore could not be explained by reference to demand characteristics or tacit knowledge. These results furthermore demonstrated an important function of image scanning, namely, to facilitate judgments of spatial relations when it is necessary for subjects to mentally extrapolate along a direction connecting objects that have not previously been observed together. Further experiments by Finke and Pinker (1983) showed that the image-scanning strategy was used only when the location of the arrow was unpredictable.

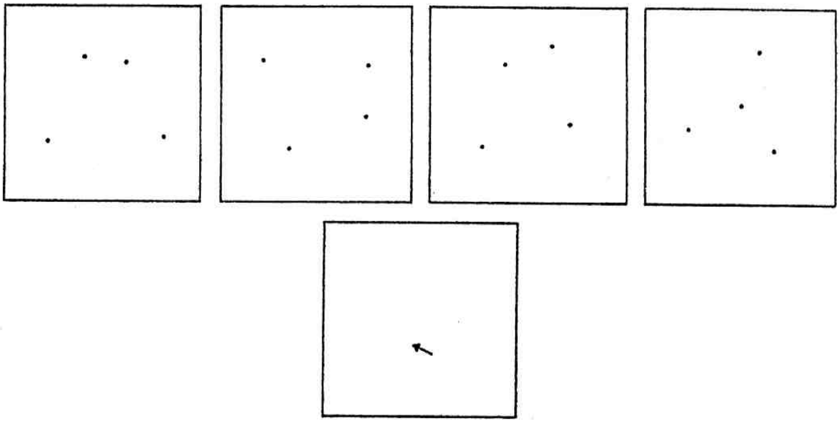


Figure 3. Dot patterns used for the experimental trials (above) and an example of an arrow stimulus (below) on which judgments of direction were made (Finke & Pinker, 1982).

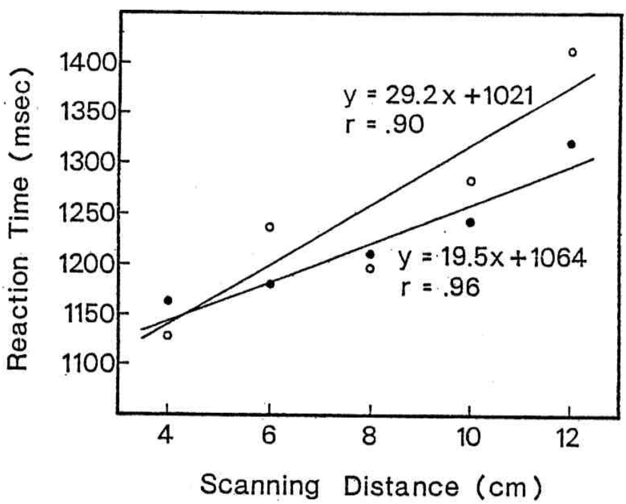


Figure 4. Response time (msec) as a function of distance separating the dot and arrow locations (cm) (Finke & Pinker, 1982). The open circles correspond to response times for the first half of trials, while the closed circles correspond to response times for the second half of trials.

In subsequent experiments, Pinker, Choate, and Finke (1984) varied the time between the presentation of the dots and the presentation of the arrow. The linear function relating distances and response times was confirmed, and the delay of arrow presentation did not alter the results. In addition, the authors found that when subjects were presented with a description of the task, they were unable to predict the form of the chronometric data and of error rates. In their last experiment, Pinker et al. (1984) had their subjects form their images from long-term memory. The subjects memorized a dot pattern at the beginning of the experiment. They kept their eyes closed, and on each trial, the arrow was presented auditorily by using a coordinate scheme (the location of the arrow was defined by a particular intersection on a previously learned 10×10 grid, and the direction in which it pointed was defined by a clockface number). The replication of the distance effect showed that people could in fact scan images reconstructed from long-term memory, and that the effect did not depend on the ongoing perception of a visual stimulus, on eye movements, or on demand characteristics.

Another interesting experimental approach was developed by Reed, Hock, and Lockhead (1983), which they used to address the tacit knowledge account of mental scanning. They asked subjects to scan images of various linear configurations, or to estimate their scan times without actually performing the scanning task. In actual scanning, the results showed that the configuration of the pattern influenced the scanning rate. Diagonal lines were scanned faster than spirals, and spirals were scanned faster than mazes. For the three patterns, however, they found consistent linear increases in scan times with increases in distance. When subjects were asked to estimate scan times, they were unable to predict the effects of different scan paths on actual scan times. This finding contradicted the hypothesis that the subjects were induced to produce the results by drawing on tacit knowledge or expectations of how scanning works. In addition, Reed et al. (1983) found that response times were not predicted by the subjects' estimates of the distance to be scanned, as would be expected if task demands led the subjects to respond more slowly when they should have scanned longer distances. The results thus are consistent with the hypothesis that subjects really do scan spatial images in the mental scanning task and do not rely on scanning times to estimate lengths.

In order to address the objection that mental scanning results reflect the subjects' responding to implicit demands in the instructions, a new method was proposed by Jolicoeur and Kosslyn (1985, Experiment 4). In their experiment, a group of subjects were presented with statements that asserted that an object or animal had a specific visible property, and asked to decide whether these statements were true or false. They were then asked to rate the statements as to the degree to which they had to use a mental image to decide whether they were true or false. The data from the true statements allowed the experimenters to assemble a total of 10 object-property pairs that reportedly required imagery to evaluate and 10 that reportedly did not. All the objects were elongated either horizontally or vertically when viewed in canonical orientation, and the property was always located at one extreme end of the object. For example, "true" high-imagery items included "*A goat has curved horns*" or "*A pineapple has pointed leaves*", whereas low-imagery items included "*A chimp has two eyes*" or "*A submarine has a metal propeller*". A second group of subjects participated in a task that consisted of forming an image of an object or animal (e.g., a goat) and focusing mentally on a particular end of it. Then, a property was named in the form of an adjective-noun pair (e.g., "*curved horns*") and the subjects were to decide whether or not the object had that property. Subjects were explicitly instructed to begin with an image and to focus on the specified location, but it was stressed that their decision about the object's property should be made as rapidly as possible without necessarily using the image. On half the trials, the queried property was on the end at which the subject was focusing and on the other half, it was on the opposite end.

The analyses of the data from the "true" trials, in which subjects would presumably have had the opportunity to "see" properties on the objects, showed that for the items that had previously been rated to require imagery, less time was needed when the subject was focused on the end where the property was located. In contrast, for the items that had previously been rated not to require imagery, the same amount of time was required for both focus locations. Furthermore, items that required imagery to evaluate required more time than those that did not. These results can hardly be explained by a demand characteristic account, given that the subjects in this experiment were never told to scan their images. Furthermore, the subjects were not told that there were two different sorts of items, and yet the subjects apparently engaged in simulating scanning only for one sort of item (the items that required imagery to evaluate). Lastly, no subject reported any insight of the actual purpose of the experiment. Thus, the data collected by Jolicoeur and Kosslyn (1985) cast serious doubts on the explanatory value of task demands in accounting for the increase of scanning times as a function of distance.

Another way to assess mental scanning was proposed by Kosslyn, Margolis, Barrett, Goldknopf, and Daly (1990), who designed a new set of materials and tasks in order to test children aged 5 to 14 and adults. In the scanning task, the subjects were presented with a stimulus shaped like a square donut, a square ring of boxes with three cells on each side and a hole in the center. On a given trial, three cells in the ring were filled in at random. The subjects studied the display that appeared on a computer screen and pressed the space bar of the keyboard when they had memorized the display. Following this, either an X or an O appeared in one of the cells of the ring. If the cue was an X, the subjects were simply to indicate whether or not it fell in a cell previously filled. If it was an O, they were to indicate whether the corresponding cell on the opposite side of the donut had been filled. In this latter case, subjects' response was supposed to require mental scanning, whereas no scanning was necessary for the former type of response. This task required mental scanning without instructions referring to scanning. The results showed that for all age groups, the subjects needed more time when scanning was required.

A variant of this task was used by Dror, Kosslyn, and Waag (1993) and Dror and Kosslyn (1994). The image-scanning task used a square-ring shape composed of white and black squares (Figure 5). After subjects studied the ring until they could remember the locations of the black squares, an arrow appeared briefly in the center of the ring, and then the entire display disappeared from the screen. The subjects had to decide whether the arrow had been pointing to a black square. The arrow was presented very briefly (50 ms), so that the subjects could not make their judgment based on the percept, but rather had to use a mental image of the display. The distance from the arrow to the square ring was varied, which should have required more or less scanning. Replicating previous results, subjects required more time to scan greater distances. Figure 6 shows the results from the Dror et al. (1993) study, in which the visuo-spatial abilities of aircraft pilots were compared with those of control subjects. Again, there was no explicit reference to scanning in the instructions. (Note that although the pilots were faster in general, they scanned at the same rate as the control subjects; apparently, scanning is not necessary in piloting, and hence pilots neither were selected to have better scanning abilities nor developed them with practice.)

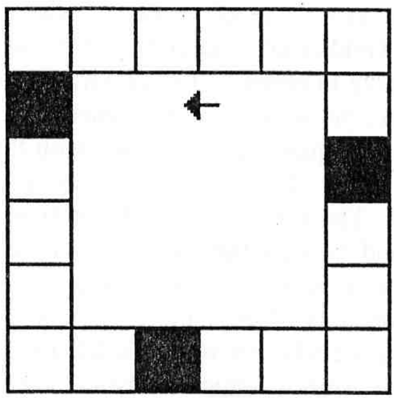


Figure 5. Example of the stimuli used in the image-scanning task (Dror, Kosslyn, & Waag, 1993).

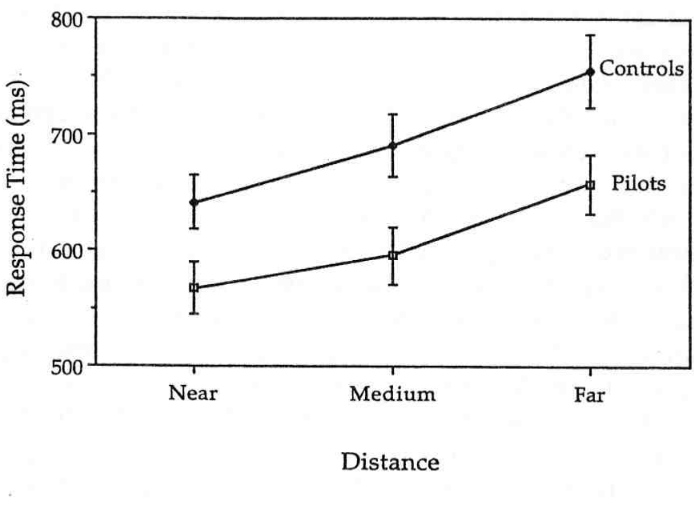


Figure 6. Response time (msec) as a function of scanning distance (near, medium, far) (Dror, Kosslyn, & Waag, 1993).

Differential and developmental approaches to mental scanning

The topic of individual differences in imagery abilities was one of the earliest concerns of scientific psychology (Galton, 1883). It is generally recognized that people differ in their capacity of forming visual images and using imagery to retrieve stored information, but the investigation of this issue has been limited because of the questionable validity of the available psychometric instruments. Imagery questionnaires and inventories have been widely used, with repeated demonstrations that subjective self-reports at least partially predict performance in imagery tasks (cf. Denis, 1982; Marks, 1973; McKelvie, 1995; Paivio & Harshman, 1983). However, when more articulated theories of imagery were proposed, stronger interest was directed towards objective measures of individual imagery abilities, especially by using visuo-spatial tests (cf. Poltrock & Brown, 1984). A modular (componential) view of imagery was defended by Kosslyn, Brunn, Cave, and Wallach (1984), in an effort to analyze imagery in terms of distinct subabilities and substitute a computationally motivated, analytic approach to the classic holistic conception of imagery. On their view, imagery is not a unitary, undifferentiated skill. Rather, it consists of a collection of distinct subabilities, which draws on a relatively small set of processing subsystems. The theory postulates that a person can be apt or bad at a given imagery ability independently of how well this person can exercise any of the other abilities.

The specific question of individual differences in mental scanning has not received in-depth consideration as an isolated phenomenon. Rather, studies taking an individual differences perspective have focused on the relationships of mental scanning to other components of mental imagery. Kosslyn et al. (1984) designed a novel image scanning task. In this task, the subjects heard the names of four objects and their relative locations (e.g., "*Briefcase; 4 inches up place a horse; 1 inch left place a beaver; 1 inch down place an onion*"), and were asked to form an image of the described scene. Once the scene was completely visualized, the subjects were asked to focus mentally on one object and then to scan to another, pressing a button as soon as they were focused on the second object. In the scanning part of that task, two processing modules were postulated to be used. According to the theory, subjects focus on the first object of the to-be-scanned pair, which is located via the FIND module. This module, which is also used in image generation, is used when a person "inspects" an imaged object for a given characteristic. When the subjects hear the name of the second object and scan to it, scanning is accomplished using the SCAN processing module, which shifts the imaged pattern across the visual buffer in a particular direction; as this occurs, the FIND processing module monitors the image so that scanning stops when the target is in focus. When the FIND module discovers that the target is in focus, a response is made.

In this particular study, Kosslyn et al. (1984) did not find any overall relationship between scan time and presumed distance. Some subjects did produce the familiar time/distance relationship, but many did not. One possibility was that subjects who did not produce this relationship had failed to produce an accurate image, one which preserved the specified distances. There was a wide range of correlations among the various tasks (from -.44 to .79). This result supported the view that subjects were not "good" or "poor" imagers in general. Furthermore, the correlation between pairs of tasks appeared to depend on the number of processing modules shared by these tasks; the more in common, the higher the correlation. These results, and those from factor analysis, supported the view that imagery is not an undifferentiated general phenomenon.

Kosslyn et al. (1990) adopted similar premises in an attempt to delineate the nature of the young child's imagery and to compare it to the imagery of older children and adults. Kosslyn and his colleagues compared the performance of 5-year-olds, 8-year-olds, 14-year-olds, and adults on four tasks which were designed to tap four imagery processes: image generation, image maintenance, image scanning, and image rotation. According to Piaget and Inhelder (1966), young children can form and use static images, but they have difficulty transforming images. Young children should then be expected to experience particular difficulty with mental rotation, and possibly with image scanning. Both rotation and scanning include a "kinetic" component, and so might be carried out by the same mechanisms. In this study, all age groups required more time when scanning was required than when no scanning was required (in the ring with X's and O's task described above). There was no difference in scanning ability between the 5- and 8-year-olds, nor was there a difference between the 14-year-olds and adults, but the youngest two groups generally scanned more slowly than the oldest two groups. Correlational analyses of performance measures on the four tasks were then conducted to discover whether the imagery processes are independent at the different ages, or whether children start off with coarse processing systems, which become articulated and more specialized with age. There were in fact no significant correlations in the response time data, a result consistent with the claim that the imagery processes tapped by these tasks are independent, and are independent as early as 5 years of age. The correlational analysis provided no evidence that the tasks could be grouped as "static" or "kinetic" at any of the ages, with members of each type sharing underlying mechanisms. The developmental approach to imagery thus provided further evidence that imagery is not a single ability, even early during development.

A study of imagery in older people was also reported by Dror and Kosslyn (1994). Young adults (aged 18-23) and older people (aged 55-71) performed four imagery tasks, each of which tapped different processes. In a mental scanning task, older people required more time and made more errors than young people, but subjects at both ages showed the standard increase in time to scan increasing distance, and the amount of increase was the same. There was no hint that older people had an impaired ability to scan or to compose images segment by segment. In contrast, the older people had relatively impaired image rotation, image activation, and ability to maintain images.

A similar dissociation between scanning and rotation abilities was reported by Dror et al. (1993), who investigated performance of people expected to have special visuo-spatial abilities. A group of US Air Force pilots was compared to nonpilots on five imagery tasks. In most of these tasks, pilots responded faster than the nonpilots. In the scanning task, pilots were generally faster, but no more accurate, than nonpilots (see Figure 6). Both groups required more time to scan greater distances, but required comparable amounts of additional time to scan each additional increment of distance, that is, they scanned images at comparable rates. On the other hand, pilots showed exceptional abilities in the mental rotation of objects, as well as in the judgment of metric spatial relations. This dissociation, taken with the ones observed over age, suggests that some processes, such as image rotation, are more plastic and thus susceptible to change, whereas other processes, such as image scanning, are less plastic.

Conclusions: What has the mental scanning paradigm contributed to our knowledge of visual mental imagery?

The mental scanning task was initially designed as a "tape measure" with which to assess whether distances are represented in visual mental images. The experiments that evoked the mental scanning process provided information on the structure of internal representations, showing that distances are represented in the form of an internal metric. The results of the experiments were inconsistent with the claim that images rely only on propositional representations that specify topological or relational spatial information. Instead, they clearly suggested that metric spatial information is represented in the mind, and that imaged objects are inspected using the same mechanisms that are used to encode and interpret objects during perception.

Further elaborations of the image theory (e.g., Kosslyn, 1994) included an analysis of mental scanning as a process. Mental scanning is conceived of as one among a collection of differentiated subabilities, and involves a type of image transformation. According to the current version of the theory, image scanning may involve two mechanisms, one that shifts the subject's attention window across the visual buffer, and one that transforms the content of the visual buffer. The notion that image scanning involves a type of transformation stems in part from the observation that when one scans an imaged scene, one never seems to "bump into the edge". Rather, scanning is continuous. In fact, Kosslyn (1978) found that the rate of scanning between two points that both were initially "visible" in the image was the same as the rate of scanning from a point that was initially visible to one that was initially "off screen". In this view, scanning is similar to what one observes on a TV screen as the camera shifts across a scene: The image seems to slide across the screen. This sort of transformation is very different from that used in mental rotation. In scanning, the entire field is transformed in a uniform way, whereas in rotation an object is selected and manipulated independently of other objects that may be present.

The objections raised by the researchers who favored propositional and/or task-demand accounts of mental imagery have been a recurrent source of inspiration for imagery researchers, who took up the challenge of inventing new methods and designs to submit such alternate accounts to empirical test. Responses from imagery researchers systematically consisted of collecting new data, which enriched the corpus of scientific knowledge on imagery processes. At the same time, imagery researchers discovered that demand characteristics may affect some aspects of their results, but they learned to develop maximal precautions against such effects.

EXTENDING THE MENTAL SCANNING PARADIGM TO CREATED IMAGES

Mental scanning originally was used simply to study the nature of visual images of previously seen objects or scenes. However, it was not long before this phenomenon was being used as a tool to investigate other kinds of questions. In this section, we review such broader uses of the mental scanning paradigm.

Mental scanning as a means of assessing the properties of images constructed from descriptions

In the research described above, researchers focused on properties of images that are closely tied to perceptual experience. Just as visual percepts are spatially extended, so are their imaginal counterparts. In more recent years, imagery researchers have become interested in images that result from *creative processes*, that is, which are not closely tied to previous perceptual experience, but are newly constructed in a cognitive task (such as text comprehension or spatial reasoning). Here, the input is typically verbal, and the subject constructs a visual image of a configuration or scene containing multiple objects.

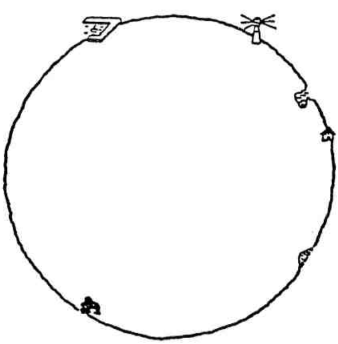
This approach was illustrated in experiments where subjects listened to the descriptions of spatial arrays containing several objects, then were required to visualize the scene as a whole (cf. Beech & Allport, 1978). The visualization of compound scenes, however, is a costly operation. Beech and Allport showed that increasing the number of objects described in the array resulted in a linear increase in visualization latency. Memory limitations were also found when subjects had to recall triplets of objects that they had learned from verbal descriptions (cf. De Beni & Cornoldi, 1985, 1988). In such experiments, however, the items in the descriptions were mentioned without any specification of their spatial relationships, or with minimal topological specifications (an object was said to be "*to the right*" or "*to the left*" of another). Language can also specify spatial relationships in more detail by including relative distance information. In some contexts, spatial descriptions may be very precise, including explicit metric information ("*The tree is 5 meters to the left of the house and 15 meters behind the church*").

Kosslyn, Reiser, Farah, and Fliegel (1983) conducted an experiment in which they examined how people construct such composites with multiple components arranged according to a description. In this experiment, subjects were presented with descriptions of scenes that contained two, three or four objects. The descriptions incorporated the terms "*above*", "*below*", "*right of*", "*left of*", and the distances "*5 feet*" and "*6 inches*". In each scene, one object was described as "floating" some specified distance and direction with respect to another object (e.g., "*The rabbit is floating 5 feet above and 5 feet left of the cup, and the violin is 6 inches below the cup*"). Two conditions were examined. In the imagery condition, subjects were to use the descriptive information to construct an image, mentally placing the objects in the correct positions at the specified distances. Then, the subjects formed the mental image of the scene. They heard a probe phrase that contained the names of two objects in the scene, connected by either "*above*", "*below*", "*right of*", or "*left of*". Subjects were to mentally focus on the first object named and then to scan straight across the image until reaching the second object named. On "seeing" the second object, the subjects were to respond by pressing one of two buttons, "*true*" if the direction of the scan was consistent with the phrase, and "*false*" if it was inconsistent. In the other (verbal) condition, subjects were told to memorize the facts contained in the description of each scene. They were told not to visualize the objects described but only to learn the facts. In the test phase, subjects were told simply to listen to the entire probe phrase and then to decide as quickly as possible whether it correctly described that scene. The results showed that more time was required to scan across a greater distance in the imaged scenes when evaluating the relative spatial position of objects, whereas no such effect was observed in the verbal condition.

The finding that people can use descriptive information to position components relative to one another in a visual image has important ramifications. In particular, an image theory must encompass those cases where subjects construct internal representations that have no immediate perceptual counterpart, and state whether such cases have any special theoretical status as compared to the more generally investigated forms of imagery. Specifically, should such images be treated as essentially different from perceptually-based images? Or do they only differ from them by the conditions of their construction, with the final product being similar in nature to those images? This is an issue to which the mental scanning paradigm can bring empirically documented answers. If images resulting from perceptual exposure to objects or configurations exhibit quasi-pictorial properties, it is an empirical matter to determine whether images constructed from verbal descriptions exhibit similar properties. By using mental scanning tasks, we have a test of the spatial qualities of images, allowing us to test the chronometric regularities likely to reflect such qualities. If different chronometric patterns are observed, this would suggest that the two kinds of images are different in nature. If, on the contrary, patterns are similar, this would substantiate the hypothesis that both sorts of images share similar properties.

Denis (1991a, 1996) and his colleagues developed a research program intended to investigate this issue in the context of a more general approach to the relation between the visuo-spatial and verbal subsystems of the human cognitive architecture. Each of these subsystems is thought to generate representations endowed with distinct properties, but recoding from one subsystem to the other is possible. Imaginal representations can be "translated" into verbal form and, more important in the context of this article, language can be used to construct visual images. These images may be rather fuzzy or inaccurate if the verbal input is incomplete or indeterminate, but provided that the verbal descriptions convey explicit information with metrically defined relationships among component parts, images may be very accurate and reach high referential value. The research program consisted of creating situations in which subjects were invited to build images of spatial configurations without perceptual cues, using only verbal descriptions. Subjects were then asked to perform mental scanning across the newly constructed images. The chronometric patterns of scanning were compared to those observed when the subjects processed images derived from actual perception. This comparison made it possible to contrast the processing of images derived from these two sources. Given the postulate that the analysis of scanning times provides an indirect, but valid and reliable reflection of the structure of visual images, the similarity between scanning patterns could justify making inferences about the internal structure of scanned images when these images are constructed from verbal descriptions.

In a first set of experiments, Denis and Cocude (1989) compared mental scanning of images that were formed on the basis of a map or a verbal description. In order to do so, they had to take several constraints into account. A first constraint was to use a configuration whose overall shape was easy to describe. For instance, the outline shape of the island used by Kosslyn et al. (1978) was far too complex to be precisely described. A much simpler, circular shape was used. The landmarks were located on the periphery of the circle, and they had the same function as the landmarks on Kosslyn's island, that is, marking the points between which scanning was to occur during the scanning test (Figure 7a). A further constraint was that the descriptive device should locate each landmark at a metrically defined point that could be described very clearly, in such a way that the subjects could assign an unambiguous location to each landmark in their images. For this purpose, the conventional directions used in aerial navigation were used, stating, for instance, that a landmark was located "*at 1 o'clock*" on the periphery of the island (Figure 7b).



(a)

"The island is circular in shape. Six features are situated at the periphery. At 11 o' clock, there is a harbor. At 1, there is a lighthouse. At 2, there is a creek. Equidistant from 2 and 3, there is a hut. At 4, there is a beach. At 7, there is a cave."

(b)

Figure 7. Materials used in Denis and Cocude's (1989) experiments. (a) Map. (b) Description.

In addition, in the description condition, learning could not be assessed by asking subjects to fill in a blank map after each trial — the method used in the original Kosslyn et al.'s (1978) experiments — since this would have provided the subjects with self-generated figural inputs, which were to be avoided in this condition. Thus, the description was learned in a fixed number of trials. A pilot experiment provided information on the number of trials needed for the subjects to draw a map indicating good memory for the configuration and the landmark locations. No more than three exposures to the description were needed by the pilot subjects. Consequently, the description was presented three times to all subjects in the description condition of the main experiment. The subjects were instructed to create as vivid and accurate a visual image of the map as possible while listening to the description. Following each presentation of the description, the subjects were required to form a visual image of the map and revise the exact location of each landmark. The scanning test replicated the Kosslyn et al. (1978) procedure. At the end of the experiment, subjects were interviewed. Those who reported having followed the image scanning instructions less than 75% of the time during the test phase were excluded and replaced. In addition, the subjects in the description condition were asked whether before mentally scanning they had relied on the location of the landmark depicted in their visual image or had first revised the hour-coded location of the landmark. In order to avoid any risk that the data reflect any contribution from strategies involving a computation based on numerical values, the subjects who reported having checked the hour-coded landmark location before mentally scanning to it were excluded and replaced.

In the first experiment, subjects who had learned the map under conditions similar to those of Kosslyn et al.'s (1978) original experiment showed the typical increase in time with increased distance scanned (Figure 8a). As a control, another group of subjects were tested in a visual (perceptual) scanning task. This control was motivated by the tacit assumption underlying most scanning experiments. The classic interpretation of the mental scanning phenomenon is that the relationship between scanning times and distances reflects the structural similarity of the image to the previously perceived configuration. This relationship is supposed to hold true in a condition where subjects perform perceptual scanning on the configuration. Until that time, however, the literature had not reported controls for this condition. Thus, Denis and Cocude

(1989) included a perceptual scanning task to ensure that perceptual scanning did exhibit the regularities that were assumed to be transferred to imaginal conditions. The results showed that the visual scanning of an actual configuration resulted in a chronometric pattern very similar to that of the mental scanning of the visual image of that configuration (Figure 8b). Indeed, the time to scan between locations on a visual configuration and a visuo-spatial mental representation that was learned perceptually increased linearly with the distance between the two locations.

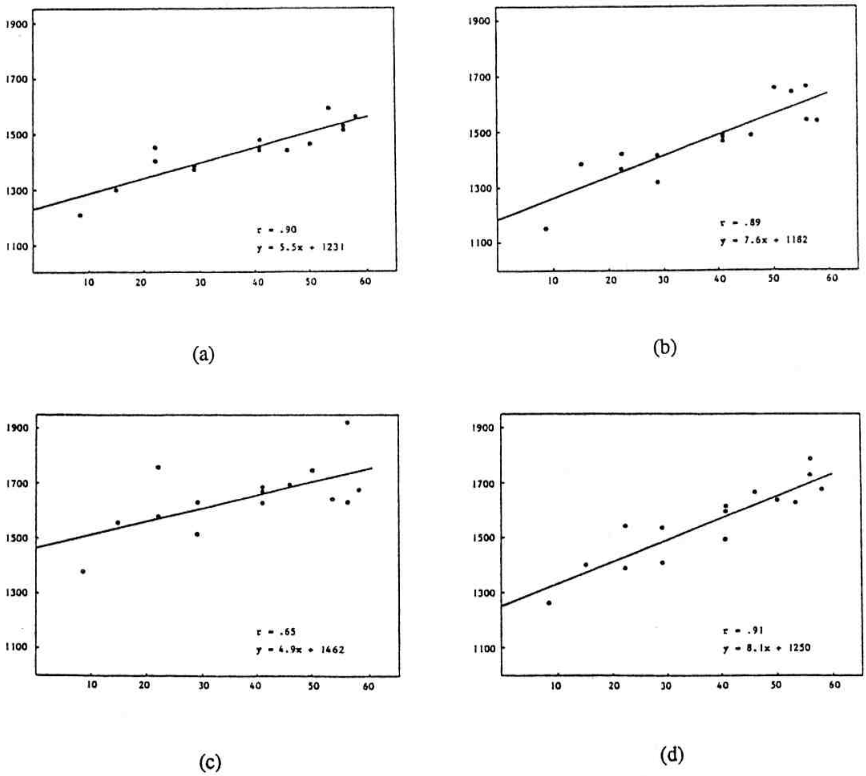


Figure 8. Response time averaged over subjects (msec) as a function of scanning distance (cm) in four conditions of Denis and Cocude's (1989) experiments. (a) Mental scanning following map learning. (b) Visual scanning of the map. (c) Mental scanning following description learning (three learning trials). (d) Mental scanning following description learning (six learning trials).

Similar linear time/distance relationship was found when subjects scanned images formed from verbal descriptions (Figure 8c). However, there were some differences in the scanning performance under the two conditions. The response times of subjects in the description learning condition resulted in a significant, but somewhat smaller time/distance correlation coefficient than those of the subjects in the map learning condition, and their absolute scanning times were also longer. Although it was established from the pilot experiment that the verbal information contained in the description was fully memorized after three trials, it nevertheless remained possible that the structural qualities of the visuo-spatial representation were insufficiently consolidated, resulting in a poorer time/distance correlation. A further experiment replicated the description learning condition, but now the subjects were given the description six times (instead of three). The differences previously observed disappeared, and scanning performance was very similar to performance following perceptual learning (Figure 8d). Thus, for a moderate rate of learning, an image constructed from a verbal description had not attained the coherence of an image derived from perception. With additional learning of the description, the image had reached a structural coherence and resolution that made it cognitively similar to a perceptually-based image.

The amount of processing of the description used to construct a mental image is only one of the factors that can affect the coherence of the image. In their last experiment, Denis and Cocude (1989) explored another factor expected to increase the similarity of description-based to map-based images. In the previous description conditions, postexperimental reports indicated that different subjects visualized the island at different sizes. Individual variability in image size may have increased the variability of scanning times. The condition based on description processing with three learning trials was thus replicated, but the subjects were now given explicit information on the size of the image to be constructed. The nominal size was that of the actual map used in the map learning condition. While listening to the instructions, the subjects were shown a blank sheet on which the map was to be imaged. The dimensions of this sheet were such that the image of the island could be inscribed on it, and be identical in size to the actual map in the map learning condition. It was expected that reducing interindividual variability through this procedure would result in a higher correlation between time and distance scanned. This correlation, indeed, was much higher than in the comparable description learning condition (with three exposures to the description), reaching a value similar to the value obtained in the map learning condition. The absolute scanning times were also substantially shorter and the variance was attenuated. These findings suggested that with a minimal amount of learning, the structural coherence of description-based images could be enhanced when explicit instructions were given to subjects on the size for image construction. In addition, this procedure substantially reduced scanning time variability among subjects.

In these experiments, as in those of Kosslyn et al. (1978), the instructions required subjects to mentally scan in the shortest straight line between the two named objects. However, one may ask whether subjects actually followed these instructions. At least some subjects may have had trouble respecting the requirement to scan in straight lines. For instance, some may have followed the periphery of the island, especially for pairs of adjacent landmarks (e.g., "*harbor*" — "*lighthouse*"). In a mental scanning experiment where subjects learned the same layout from a description, Denis and Zimmer (1992) calculated the correlation coefficient between times and distances in two ways. The first (standard) calculation used the straight line distances, and resulted in a significant time/distance correlation coefficient (r = .90). For the second calculation, straight distances between adjacent objects were replaced by the corresponding distances of the curved path. If subjects really performed this way, then the coefficient should have increased. It turned out, in fact, that the coefficient did not increase, but rather decreased (dropping to r = .81). It can therefore be reasonably assumed that subjects actually followed straight paths between landmarks during mental scanning.

A further point of interest concerns the variances of scanning times for the different distances. In particular, would variances be larger when longer distances are processed? This relationship, if shown, would reflect a greater amount of uncertainty for the scanning process when it deals with more remote landmarks. As a consequence, it would suggest that times for these distances are contaminated by some amount of noise. In fact, no such relationship was evident. There was no significant correlation between distances and variances of times. This result lends additional support to the claim that mental images constructed from descriptions are likely to exhibit reliable metric qualities.

The Denis and Cocude (1989) experiments provided the first demonstration that mental images generated from descriptions have genuine metric properties, which were reflected by the same chronometric pattern of mental scanning processes that is found when people scan images based on perceptual inputs. The evidence that images constructed from verbal descriptions include metric properties is an especially interesting feature, because it shows that these images contain *more* information than the explicit information given in the descriptions. Not only did images contain information on the nature and locations of the geographical landmarks (information that was effectively conveyed by the descriptions, such as information that there is a harbor at a given location), but also contained information about the relative distances among landmarks, even though the descriptions said nothing about these distances and subjects had no direct access to this information. The capacity of description-based images to display non-explicit information derives from an important representational property inherent in visual imagery, that is, specifying locations of subparts of the representation makes the relative positions of these subparts evident.

Effects of the structure of descriptions on the construction and scanning of mental images

The Denis and Cocude (1989) data support the claim that images generated from descriptions have structural properties that are characteristic of images derived from perceptual experience. But the two sorts of images need not be entirely equivalent. The equivalence of images generated from perception and from descriptions could be restricted to their geometrical properties. Other properties, such as clarity or vividness, may be differently expressed in perceptually and verbally-based images. Note also that in the Denis and Cocude (1989) experiments, the specific pace of learning and the regular sequence used for the description probably helped the image achieve the same structural coherence as when it was constructed from visually studying the map.

Thus, Denis and Cocude (1992) next tested the sensitivity of the mental scanning paradigm to experimental variations that were likely to make it more difficult to build a coherent, integrated image. The effects of discourse structure on the construction of mental representations of spatial configurations are well established. In particular, the specific order in which information is entered in descriptions is known to affect the on-line construction of internal representations, and hence their availability for retrieval (cf. Denis, 1996; Denis & Denhière, 1990; Ehrlich & Johnson-Laird, 1982; Mani & Johnson-Laird, 1982). Thus, whereas a well-structured description was used in the Denis and Cocude (1989) experiments, with landmarks presented in a predictable, consistent clockwise sequence, Denis and Cocude (1992) investigated whether subjects could construct effective, scannable representations from poorly structured descriptions. A new version of the description was constructed by simply presenting the same sentences as in the previous experiments in a random sequence. This new set of experiments was also intended to study image construction at different steps in description learning. Unlike the previous experiments in which different subjects performed the mental scanning task after three or six learning trials, in the new experiments the same subjects took part in each successive step of the experiment. Subjects thus participated in three learning trials before performing the first mental scanning task. They then resumed learning for three more trials, and performed a second scanning task.

Analysis of response times revealed that the subjects who processed the clockwise description produced responses reflecting structural coherence of their images in the first scanning task, as indicated by a significant positive correlation between times and distances. After additional exposure to the same description, in the second scanning test the time/distance correlation was slightly higher while the absolute scanning times were lower. The pattern of results was strikingly different for the subjects who received the random description. The results of the first scanning test gave no suggestion that the subjects' mental images possessed any internal structure. Response times were very long, and there was no significant correlation between scanning times and distances. The situation changed markedly after three more exposures to the description. Scanning times were much shorter and there was now a significant positive correlation between times and distances.

These findings confirmed that images generated from verbal descriptions can exhibit metric properties similar to those of images derived from perceptual inputs. They also demonstrated that the structure of a description affects the intrinsic structure of images of described objects, and hence the mental operations subsequently performed on these images. The subjects still showed the standard time/distance correlation when the description was poorly structured, but they required more learning before it was evident. In contrast, a well-structured description, which placed minimal requirements on the subjects' processing capacities, rapidly yielded accurate, well integrated representations as well as more pronounced correlation between time and distance. These results indicate that the referential validity of images (i.e., their capacity to reflect accurately the objects they refer to), is not an all-or-nothing property, but results from stepwise elaboration.

The gradual construction of visual images was investigated in more detail in a subsequent experiment. Denis, Gonçalves, and Memmi (1995) developed a model to account for the gradual process of image elaboration and the progressive increase in image accuracy. The model posited that the location of a landmark mentioned in a description is not represented as a sharp point in the mental image, but is instead associated with a region around this point. The region represents the possible range of the landmark's location at a given stage of the learning process. Learning the description essentially consists of progressively narrowing each "region of uncertainty" associated with a landmark to its exact location. The size of the unfocused regions is expected to vary inversely with the degree of image elaboration. The closer the image is to its ultimate step of elaboration, the more restricted these regions are.

Additional data were collected to provide a more fine-grained understanding of image elaboration. In the Denis and Cocude (1992) experiment, the subjects heard the description six times and received two scanning tests (one after three exposures and the other after three more exposures). In the new experiment, subjects heard the descriptions the same number of times, but there was a total of three mental scanning tests, one after each pair of learning trials. The procedure thus provided three successive "views" of the mental representation under construction. The subjects were presented with the description in random order, which was expected to show the most dramatic effects.

The scanning times for the first test were longer than in the second test, and the times further decreased between the second and third tests. In addition, there was no correlation between time and distance for the first scanning test, but the coefficients reached significance for the second and the third tests (Figure 9). The results of the first scanning test revealed no structure at all in the image under construction. Response times were extremely long. Obviously, two exposures were not enough for subjects to construct a coherent, accurate image, and mental scanning revealed no sign of the metric properties of the imagined map.

Two more exposures changed the situation dramatically. Subjects produced chronometric patterns that revealed that metric information was specified in the images. The times were also significantly shorter, a finding compatible with the assumption that the images had an internal structure which was more readily available. The process was even more marked after the final two exposures. The numerical values at the third test (scanning times as well as correlation coefficients) indicated further improvement in the internal structure of the image.

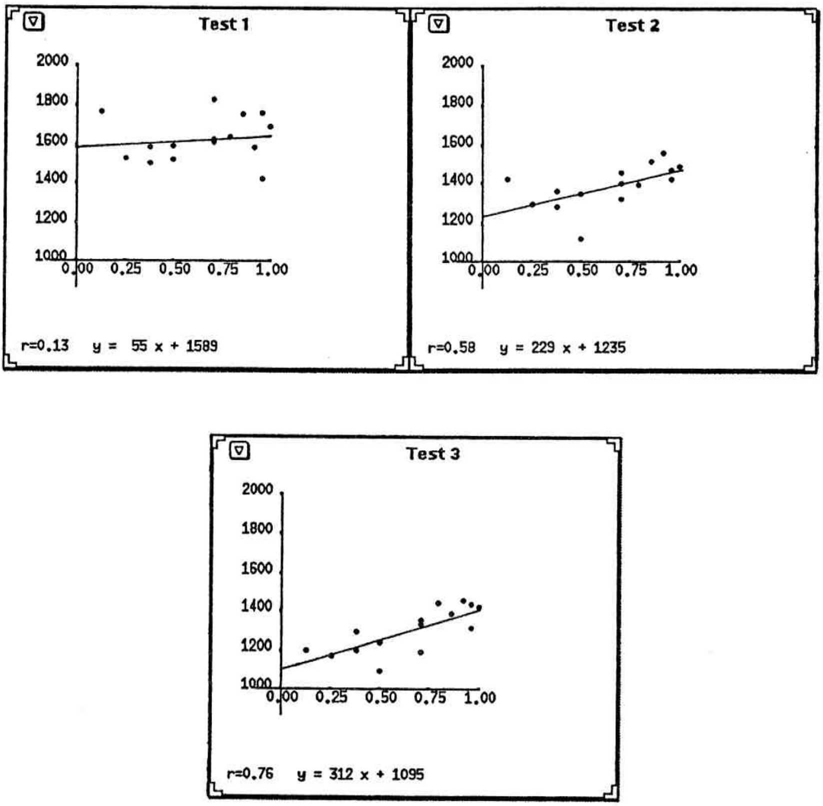


Figure 9. Response time averaged over subjects (msec) as a function of scanning distance in three successive tests (Denis, Gonçalves, & Memmi, 1995). Distances are expressed as their ratios to the diameter of the island.

The model of image accuracy was applied to the data to discover whether the analysis reflected a stepwise restriction of regions of uncertainty in the mental image, and whether such restriction was more evident between the first and second tests than between the second and third. Individual scanning times for every distance separating a pair of landmarks were used to compute values reflecting the sizes of regions of uncertainty. The underlying logic was that these times could be used in conjunction with a measure of each subject's individual scanning speed to compute the distances theoretically scanned during these times. Each of these distances was thus compared with the actual distance separating the corresponding pair of landmarks, which made it possible to calculate the error in the location of the landmark. First, each subject's scanning speed was calculated, using measures of the third scanning test as references. Each individual scanning time for a given subject in each test was then used to compute a corresponding estimated distance based on individual speed values. The distance was compared to the actual distance and the corresponding error was calculated. The scanning time used for a given distance was an average value for both scanning directions (e.g., "*lighthouse*" — "*harbor*" and "*harbor*" — "*lighthouse*"). The error was thus distributed evenly between the two landmarks. A total of five error values were calculated for each landmark (because there were six landmarks, any given landmark was involved in five distances). The error was expressed in terms of the ratio to the diameter of the island. Corresponding values were then entered as radii of circles reflecting the region of uncertainty associated with each landmark. The regions of uncertainty for each individual subject were expressed graphically as circles centered on the exact point of each landmark. Averaging values over subjects for each scanning test in each condition resulted in graphic representations of the regions of uncertainty for the three scanning tests (Figure 10).

Inspection of the data first revealed that the sizes of regions of uncertainty (i.e., the reciprocal of accuracy) varied widely among landmarks. Overall, the landmarks in the part of the map that had the greatest density of landmarks tended to be located most accurately (i.e., by smallest regions of uncertainty). This result was consistent with the assumption that landmark location is favored when a landmark has close neighbors. Isolated landmarks were less accurately located at the outset. The other feature of interest was that the size of regions of uncertainty decreased after each new exposure to the description. This decrease occurred for all regions, although it was more marked for some of them. As expected, there was a greater decrease between the first and second tests than between the second and third. The fact that there was a slight additional restriction of regions of uncertainty between the second and third tests confirmed that there can still be a further improvement in image coherence and resolution even when the verbal description is fully memorized.

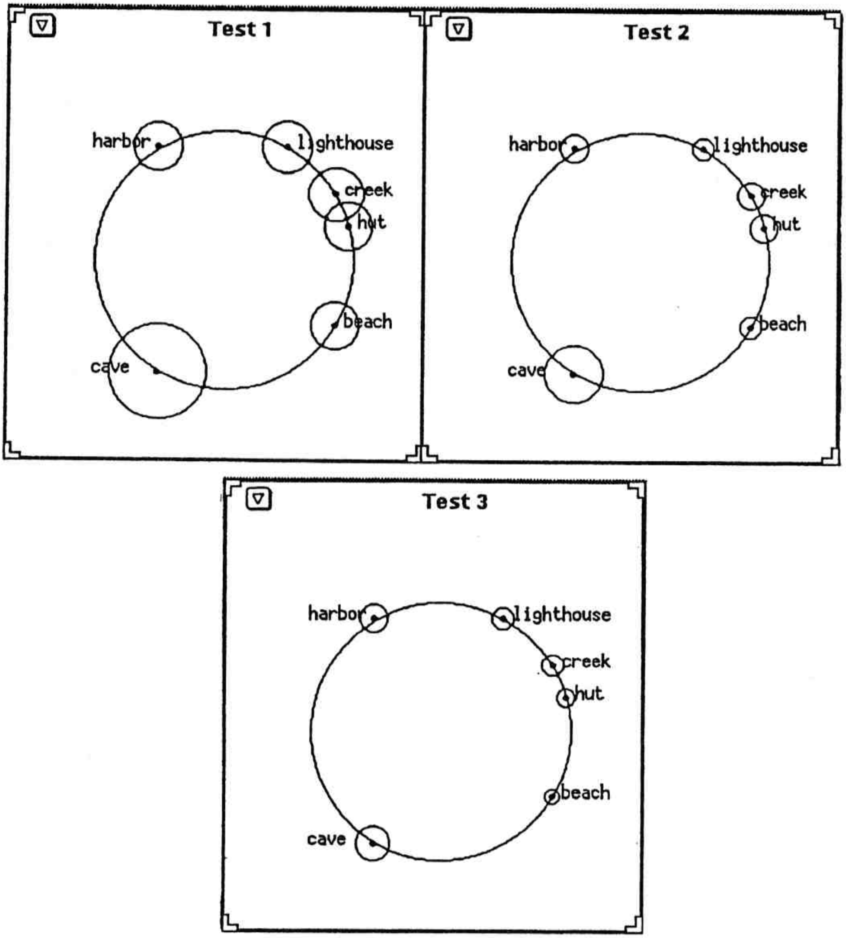


Figure 10. *Graphic representations of regions of uncertainty (Denis, Gonçalves, & Memmi, 1995).*

Semantic effects and the role of individual differences

The mental scanning experiments described above focused primarily on the spatial (metric) properties of the objects represented. They did not consider the possible effects of the semantic content of landmarks. For instance, "*harbor*", "*lighthouse*", and so on, were used simply as labels of points. However, in memory of real-world spatial configurations, the structure of mental representations is known to depend to some extent on knowledge, experience, and the value attached by the subjects to the landmarks. For example, subjects required to estimate distances in natural environments tend to underestimate distances between them and a well-known landmark or a landmark with which they have had repeated interactions. In contrast, people tend to overestimate the distances to less frequently visited landmarks (cf. Byrne, 1979; Moar & Bower, 1983).

Denis and Cocude (1997) examined the sensitivity of the mental scanning paradigm to descriptions in which some of the landmarks were rendered particularly salient. The objective was to determine whether a specific manipulation of the description could lead to systematic biases in the representation constructed from it, as in real-world configurations. Here again, mental scanning was thought to tap the differential availability of landmarks. Experimentally induced biases could reveal their effects through scanning times differing from those recorded previously.

The first experiment devoted to this issue ensured that three of the six landmarks on the periphery of the island would be processed in a particular way. The description of each landmark not only gave information about its location, but also provided a short narrative containing many concrete details about it. This narrative was designed to increase the salience of the landmark. The other three landmarks were described in a neutral fashion. Subjects learned the descriptions and then performed the mental scanning task. The results showed that there was no difference between the scanning times towards important landmarks and secondary ones, and the time/distance correlation coefficients were virtually identical, whatever the type of scanning. Apparently the locations of the landmarks *per se* governed scanning times in this task.

The importance of the landmarks was then manipulated by including additional descriptions that referred to imaginary actions of the subjects themselves in the landmarks (the subjects had to imagine their own activities in three landmarks, while the other three landmarks were described in neutral terms and did not imply any associated activity). This manipulation also produced no differential effect on scanning times, or on correlations. Lastly, the descriptions of three of the six landmarks were enriched by colorful pictures designed to give these landmarks greater cognitive salience. The results still revealed no significant effect of the salience of the landmarks. Thus, on the whole, experimental attempts to modify the salience of landmarks in materials newly learned by subjects from a verbal description did not result in measurable representational biases.

Lastly, the sensitivity of mental scanning to subjects' individual characteristics was examined. The studies reported above indicated that subjects differ in their mental scanning performance (cf. Dror et al., 1993). The experiments conducted by Denis and Cocude (1997) investigated the effects of individuals' imagery capacities on the mental scanning of images constructed from a verbal description. The subjects of these experiments were asked to complete the Minnesota Paper Form Board (MPFB; Likert & Quasha, 1941), a visuo-spatial test widely used in imagery research. They were split into two groups, those who scored above and those who scored below the median of scores. Thus, the subjects who were mostly apt at generating and manipulating visual images were compared to subjects less prone to imaging.

The results were very different for the two groups of subjects. The subjects with high visuo-spatial capacities produced the typical mental scanning results (relatively short scanning times and a significant time/distance correlation coefficient). In sharp contrast, the subjects with poorer visuo-spatial capacities showed no evidence that their images had stable, consistent structural properties. Their scanning times were long, and there was no consistent relationship between scanning times and distances. These results were reminiscent of those from people who had just begun to learn verbal descriptions in the earlier experiments. This pattern suggested that these subjects had much difficulty controlling the generation and inspection of their images.

Conclusions: Knowledge acquired from recent variations on the mental scanning paradigm

Imagery is a cognitive tool for dealing with absent objects. A considerable range of capacities becomes available when a cognitive system can create representations that are independent of immediate or recent perceptual experience, either from externally-provided instructions (as in most of the situations considered above) or from purely endogenous processes (which correspond to those capacities that the commonsense concept of "imagination" subsumes). In both cases, a cognitive system enjoys the possibility of "looking at" and "manipulating" novel, newly created mental objects. In short, these capacities provide people with the possibility of preparing to interact with hypothetical worlds.

Mental scanning studies have shown that newly constructed images are not unstructured patterns. They possess a structure that reflects great similarity with the structure of representations that arise from perception. Information is distributed in a depictive way, exhibiting genuine metric properties. This feature has important consequences. In particular, a person can operate mentally on internal representations that are composites of images derived from perception and internally-generated images. The possibility of manipulating composite images is a further extension of human cognitive capacities.

Lastly, these studies have shown that mental images are constructed progressively. Before the terminal state where an image reaches its ultimate structure, the image passes incrementally through successive states where its metric structure is not fully evident. Mental scanning measures make it possible to capture the progress in firming up the structural qualities of an image, from an initial state where this structure is absent to an end state where it is achieved. Thus, mental scanning has proven to be a useful method for studying the intimate structure of mental images.

NEUROIMAGING STUDIES OF MENTAL SCANNING: A PROMISING APPROACH

In addition to the behavioral evidence that visual imagery and perception share functional properties, neuropsychological findings suggest that the two systems involve common brain structures (e.g., Basso, Bisiach, & Luzzatti, 1980; Farah, 1984; Farah, Levine, & Calvanio, 1988). The involvement of cortical structures common to visual imagery and perception is also indicated by studies of evoked potentials (cf. Farah, 1995; Farah, Weisberg, Monheit, & Péronnet, 1989) and regional cerebral blood flow (e.g., Goldenberg, Podreka, Steiner, Willmes, Suess, & Deecke, 1989; Kosslyn, Alpert, Thomson, Maljkovic, Weise, Chabris, Hamilton, Rauch, & Buonanno, 1993). Some findings, however, have raised doubts that visual imagery and visual perception use the same neural substrate. The most significant are those showing that brain-damaged patients with severely impaired object recognition may have fully preserved visual imagery (e.g., Behrmann, Winocur, & Moscovitch, 1992). Moreover, some patients with visual imagery disorders apparently have no perceptual disorder (e.g., Guaraglia, Padovani, Pantano, & Pizzamiglio, 1993). The double dissociation between imagery and perception in brain-damaged patients may indicate that forming visual images relies on top-down processes that are not necessary in perception, and perception relies on bottom-up organizational processes that are not necessary in imagery.

Because mental scanning is a relatively well-understood phenomenon, it can profitably be used to investigate the role of different parts of the brain in information processing. Little information is available on the brain structures that are involved in mental scanning specifically. The first neuroimaging study on the mental scanning of images of described objects used single photon emission computerized tomography (SPECT). It was conducted by Charlot, Tzourio, Zilbovicius, Mazoyer, and Denis (1992), and included an investigation of the effects of individual differences in imagery capacities on brain activity. Two visuo-spatial tests, the MPFB and the Mental Rotations Test (Vandenberg & Kuse, 1978), were used to select two groups of subjects, one with high and the other with low visuo-spatial capacities (corresponding to the upper and lower thirds of scores on both tests). The subjects first learned a verbal description of the map of the island used in the Denis and Cocude (1989) experiments. The description introduced the landmarks in clockwise order, and was presented three times. Subjects then took part in two cognitive tasks (in addition to a rest condition). One task consisted of mentally conjugating abstract, irregular verbs. The other task was reconstructing the visual image of the island and performing mental scanning of the distances separating the landmarks. Upon hearing the name of one landmark, subjects were asked to mentally fly from this landmark to each of the other five and return, while maintaining as vivid a visual image as possible. Because of the technical constraints of this type of experiment, chronometric measurements of individual scanning performances were not possible.

High visuo-spatial imagers showed a selective increase in blood flow in the left sensorimotor cortex, relative to the resting state, while performing the verbal task, whereas there was a significant increase in blood flow in the left temporo-occipital cortex when they imagined and mentally scanned the visual configuration. This result was compatible with the notion that mental representations reconstructed from visual experience and those constructed from spatial descriptions involve the same cortical areas. In contrast, the low visuo-spatial imagers showed much less clearly differentiated increases in their cerebral blood flow.

One further study that looked specifically at the brain activity associated with mental scanning was reported by Mellet, Tzourio, Denis, and Mazoyer (1995). This study used positron emission tomography (PET). In the learning phase, subjects were asked to inspect and memorize the map of an island similar to those used in previous experiments, with landmarks located on the periphery of the map. Regional cerebral blood flow was then recorded as the subjects performed a perceptual and an imagery version of the task. In the perceptual condition, the subjects were shown the map and asked to scan visually from landmark to landmark alternatively in a clockwise and then a counterclockwise direction. In the imagery condition, the subjects were placed in total darkness and were instructed to recreate a vivid image of the map, then perform mental scanning from landmark to landmark by following the same procedure. Brain activity was recorded during the two scanning tasks and compared to a rest condition.

The results clearly indicated that scanning in both conditions involves a common network of cerebral structures, including a bilateral superior external occipital region and a left internal parietal region (precuneus). The occipital region seems to be responsible for the generation and maintenance of the visual image, whereas the parietal region is likely to be involved in the scanning component of the process. Other PET studies have also indicated that memory-related imagery is associated with precuneus activation (e.g., Fletcher, Frith, Baker, Shallice, Frackowiak, & Dolan, 1995). Another finding was that bilateral activation of the primary visual areas occurred in the perceptual condition, but these areas were not activated during mental scanning in the imagery condition (for a detailed discussion of the circumstances in which imagery activates the primary visual area, see Thompson and Kosslyn, in press).

The fact that regions of the "dorsal system" (which runs from the occipital lobe to the parietal lobe) were activated during the mental exploration of a previously learned visual configuration is consistent with long-held conceptions of the role of the parieto-occipital cortex (e.g., Andersen, 1987). Indeed, Levine, Warach, and Farah (1985) and Farah, Hammond, Levine, and Calvanio (1988) found evidence that mental images respect the dichotomy between the dorsal system, which processes spatial attributes of visual stimuli (such as location, size, and orientation), and the "ventral system", which runs from the occipital lobe and the inferior temporal lobe, and is responsible for processing figural attributes (such as shape, color, and texture; e.g., see Haxby, Grady, Horwitz, Ungerleider, Mishkin, Carson, Herscovitch, Shapiro, & Rapoport, 1991; Ungerleider & Mishkin, 1982). Moreover, in a task where subjects constructed mental images of cube assemblies from verbal instructions, PET recordings provided evidence that the dorsal route was recruited by linguistic stimuli in the absence of any visual input (cf. Mellet, Tzourio, Crivello, Joliot, Denis, & Mazoyer, 1996). This is an important finding because it indicates that the role of the dorsal route in spatial processing is not linked to the modality in which information is presented. The same network is apparently engaged in both mental scanning of visual images and the creative construction of purely mental objects.

The hypothesis that the dorsal system is involved in the mental scanning of imagined visuo-spatial configurations received further support from a case study reported by Morris and Morton (1995; Morton & Morris, 1995). The patient, MG, suffered a left parieto-occipital lesion and had a selective deficit in visuo-spatial processing. Her visual memory was not impaired at all, as reflected by good performance in face recognition and other visual memory and image inspection tasks. In contrast, her performance was significantly impaired in tasks that required active processing of visuo-spatial information. In particular, MG was impaired on several mental rotation tasks. When she was tested in an adapted version of the Kosslyn et al. (1978) Experiment 2, MG was able to learn the map of the island and to draw the landmarks at their correct locations. However, when asked to perform scanning, she reported that she was only able to generate images of the individual landmarks, and was unable to switch her attention across the map from landmark to landmark. Impairment in image scanning was confirmed in another task, which consisted in scanning the contour of block letters.

Another domain in which mental scanning can illuminate the nature of brain processes is the mental exploration of memorized geographical configurations (cf. Ghaëm, Mellet, Crivello, Tzourio, Mazoyer, Berthoz, & Denis, 1997; Ghaëm, Mellet, Tzourio, Bricogne, Etard, Tirel, Mazoyer, Berthoz, & Denis, 1998). In the Ghaëm et al. (1998) study, subjects learned a city map of a real urban environment by repeated inspection of the map. The learning procedure was basically the same as the procedure used by Kosslyn et al. (1978) and Denis and Cocude (1989). Learning ended when the subjects were capable of locating accurately seven landmarks on the map. Then, during the PET session, the subjects performed mental scanning between all possible pairs of landmarks. They were asked to mentally scan along the streets (which required following curved paths in some cases), but the subjects were required to perform mental scanning along the shortest street route in all cases. A highly significant positive correlation coefficient was calculated between scanning time and distance, which indicated that the visual image of a realistic map contained accurate metric information, just as did the visual images of the schematic, fictitious environments used in previous research.

The PET recordings were compared to recordings in three control tasks. The main result was that mental scanning involved the activation of a fronto-parietal network similar to the network involved in the execution of memorized eye saccades (cf. Petit, Orssaud, Tzourio, Crivello, Berthoz, & Mazoyer, 1996). Ghaëm et al. (1998) also found that the hippocampal regions were involved in the mental scanning of an imaged map as in mental navigation subsequent to actual experience of an environment (cf. Aguirre & D'Esposito, 1997; Ghaëm et al., 1997; Maguire, Frackowiak, & Frith, 1996).

It seems clear that a complex system is used in image scanning, and the precise mechanisms may depend on the context of the task as a whole. The theory of Kosslyn (1994) suggests that image scanning involves two distinct mechanisms. One mechanism shifts attention covertly, so that different portions of a representation are processed in detail. The other mechanism is a type of image transformation. The analogy here is to what one sees on a TV when the camera shifts across a scene; the image seems to shift incrementally across the screen. This mechanism would allow one to scan continuously in any direction. Most scanning may involve a mixture of these two mechanisms. Moreover, the processes that direct the scanning themselves may be complex. In some cases, one may direct scanning along a particular spatial vector, which would rely on dorsal processing. In this case, memories of specific visual patterns would not play a key role in processing, and hence there would not be activation in the ventral system and hippocampus. In other cases, however, one may anticipate what one would see in a certain direction, in which case the process may rely on the ventral system. In this case, scanning would result from a kind of "priming", in which an image is replaced by another that one would expect to see if scanning in a particular direction, which in turn would be replaced, and so on (in small increments). In this case, memory would play a key role, and hence hippocampal activation would be expected. Again, the two types of processes may often work together. Thus, what might appear to be a simple process, image scanning, is in fact probably complex. The results from the available experiments are consistent with this conclusion.

CONCLUSIONS

Mental scanning has evolved from a topic in its own right to a tool that can be used to address other topics. The initial research focused on the methods and the basic phenomenon, and showed that mental scanning does in fact tap structural properties of the underlying image representation. The fact that many experiments were conducted to rule out various alternative accounts leads us to be confident in the use of this technique for other purposes. Those other purposes have focused to date on the interface between language and imagery, and have concentrated on studying the process whereby descriptions can be converted into images.

The recent use of mental scanning in neuroimaging studies holds out two kinds of promises. First, we should be able to understand in greater detail exactly how mental scanning operates, and its relation to actual perceptual scanning. By examining the neural foundations of scanning we can further distinguish different sorts of scanning, and also further distinguish scanning from other types of cognitive operations; if different patterns of brain activation are evoked in two tasks, by definition they cannot be relying on identical processes. Second, by studying the neural underpinnings of image scanning, we will further understand the functions of specific brain areas. Because so much is now known about mental scanning, by comparing the effects of various manipulations on brain activity we should be in a good position to begin to draw inferences about the specific roles of different neural structures.

In summary, what began as a controversial topic in experimental psychology has now settled into a tool used routinely in neuroimaging studies. To our mind, this is evidence of genuine scientific progress.

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RÉSUMÉ

Le processus d'exploration mentale correspond au déplacement systématique de l'attention sur l'image visuelle d'un objet. La première partie de cet article aborde l'exploration mentale comme méthode expérimentale permettant de mettre en évidence les propriétés structurales des représentations mises en oeuvre dans l'imagerie mentale visuelle. La théorie de l'imagerie à laquelle nous nous référons postule que les images visuelles reflètent les propriétés métriques des objets imaginés. Il résulte de cette hypothèse que le temps nécessaire pour parcourir mentalement une distance sur un objet imaginé doit être d'autant plus long que cette distance est plus grande. De tels résultats ont été rapportés dans de nombreuses études. Ces résultats, toutefois, ont fait l'objet de controverses et d'interprétations alternatives, qui ont inspiré à leur tour de nouvelles études. Notre revue met l'accent sur le fait que ces interprétations méritent elles-mêmes d'être discutées et que les résultats des expériences d'exploration mentale ont toutes chances de refléter les propriétés métriques des représentations mises en oeuvre dans l'imagerie, suggérant ainsi que l'imagerie utilise des mécanismes similaires à ceux de la perception visuelle. La seconde partie de l'article se focalise sur l'exploration mentale comme méthode permettant d'examiner si le trai-

tement de descriptions verbales permet de construire des images reflétant des propriétés structurales similaires à celles des images d'objets effectivement perçus. Il s'avère que des images construites à partir de descriptions d'objets qui n'ont jamais été perçus possèdent une structure semblable à celle des représentations construites à partir d'une expérience perceptive. Les expériences d'exploration mentale permettent également d'identifier les caractéristiques des descriptions verbales susceptibles d'être transformées le plus aisément sous forme d'images visuelles. Enfin, nous examinons l'utilisation du paradigme de l'exploration mentale dans des études de neuroimagerie. En étudiant les mécanismes nerveux qui accompagnent l'exploration mentale, il est possible non seulement de mieux comprendre les processus d'imagerie mentale, mais aussi de circonscrire les mécanismes cérébraux qui les soustendent.

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